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ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT

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REPORT 263

EXPERIMENTAL RESEARCH ON THE MECHANISM OF TRANSITION

by

E. MATTIOLI and G. ZITO

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CORRECTION TO REPORT 263

'EXPERIMENTAL RESEARCH IN THE MECHANISM OF TRANSITION'

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Please note that Part I of the above Report was prepared solely by E. Mattioli. G. Zito contributed Part II.

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This Report is one in the Series 253-284 of papers presented at the Boundary Layer Research Meeting of the AGARD Fluid Dynamics Panel held from 25-29 April 1960, in London, England

SUMMARY

This Report describes experimental research on transition in an incompressible fluid in a smooth straight pipe. At constant delivery there is an intermittent state in which the flow is laminar at the inlet of the pipe and intermittent at the outlet - so-called turbulence spots preceded and followed by laminar flow. The inner transition in the pipe (with laminar inlet and turbulent outlet) occurs through an intermittent zone and an incipient turbulent zone. The main characteristics of these spots are discussed and methods are described for assisting or preventing transition. Also dealt with are the sinusoidal speed waves caused by screens, and the acoustic signals produced by the presence of a hot-wire. The difficulties of measuring the intermittence factor are also discussed.

An Appendix describes an electronic instrument designed for measuring the intermittence factor, together with a proposed method of control for obtaining standard measurements.

SOMMAIRE

Ce rapport est consacré à l'étude expérimentale de la transition dans des tuyaux lisses et droits en écoulement incompressible. A débit constant, il existe un régime intermittent dans lequel l'écoulement est laminaire à l'entrée du tuyau et intermittent à la sortie (désigné siège de turbulence précédé et suivi de l'écoulement laminaire). La transition interne dans le tuyau (entrée laminaire et sortie turbulente) intervient à travers une zone intermittente et une zone de turbulence naissante. Les principales caractéristiques de ces sièges turbulents sont examinées, avec indication des moyens favorisant ou interdisant la transition. Sont également discutées les ondes sinusoidales de vitesse provoquées par des grillages, et les signaux acoustiques dûs à la présence du fil chaud. Les difficultés que soulève la mesure du coefficient d'intermittence sont indiquées.

On décrit dans un annexe un dispositif électronique de mesure du coefficient d'intermittence, ainsi qu'une méthode de régulation du dispositif permettant d'obtenir une normalisation des résultats des mesures effectuées.

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NOTATION

r	radius of pipe (in experiments with air, $r = 1$ cm)
d	diameter of pipe
l	length of pipe
p	pressure
p_s	static pressure
p_t	total pressure
U	local average speed
U_m	average speed (= delivery/πr^2). For laminar flow, $U_m = \frac{1}{2}U_{max}$; for turbulent flow, $U_m = 0.78\ U_{max}$
U_{max}	maximum speed at centre of pipe
u	component of speed fluctuation along x-axis
u'	$= \sqrt{(\overline{u^2})}$
x	abscissa along a pipe generator, measured from tube inlet
y	ordinate along a pipe diameter, measured from wall
(x, y)	co-ordinates of hot-wire in oscillograms
(x_1, x_2)	abscissae of upstream wire (1st) and downstream wire (2nd) in the two beam oscillograms; both wires at centre of pipe
Γ	intermittence factor (i.e. ratio of duration of turbulent signal to total duration)
γ	coefficient of resistance ($= \tau/\frac{1}{2}\rho U_m^2$)
τ	coefficient of skin friction at wall ($= dp/dx \times \frac{1}{2}r$)
μ	coefficient of viscosity
ρ	density
ν	coefficient of kinematic viscosity
$\cdot$	time signals on oscillograms (interval = 0.1 sec)

EXPERIMENTAL RESEARCH ON THE MECHANISM OF TRANSITION

E.Mattioli and G.Zito*

1. INTRODUCTION

In the past few years more attention has been paid to the problem of transition in the boundary layer than to transition in the pipe itself. Some of the more important of these researches are those of Schubauer and Klebanoff[1], Emmons[2], Townsend[3], Corsin and Kistler[4], and Skramstad.

This Report deals with more recent research on the initiation of turbulence in incompressible flow in smooth pipes and some of the main results and difficulties encountered in this work are discussed. The work was carried out at the Aerodynamics Institute of the Politecnico di Torino, Centro Studi sulla Dinamica dei Fluidi (Consiglio Nazionale delle Ricerche), under the direction of Professor C. Ferrari.

It is well known that there is a critical value of Reynolds number ($R_{e\ crit}$) below which the flow always becomes laminar again after any disturbance, but laminar motion for Reynolds numbers much higher than $R_{e\ crit}$ can also be obtained. This explains both the uncertainties that exist about the exact value of $R_{e\ crit}$ (assumed to be about 2000) and the difficulties of ascribing any quantitative rules to the factors causing transition.

To make the transition visible, experiments were carried out in a plexiglas pipe (of diameter 8.5 mm) using a low-viscosity silicone ($\nu = 1.5 \times 10^{-6}$ m^{2}sec). A quantity of aluminium powder was dissolved in the silicone to make the streamlines visible.

The tests were carried out by the hot-wire method (10% Rhodium Pt core, with a diameter of 2.6 microns, supplied by the Sigmund Cohn Corporation). The pipe was of highly polished brass and had an inside diameter of 20 mm. The first series of experiments was done with parts of different lengths fitted into one another. Later, in order to avoid even the small misalignments due to the steps in the pipes, a single pipe was used, 3 metres long. This was provided with 9 measuring stations (Fig.1).

Air was supplied through a drying apparatus, from a tank of 500 litres capacity at 10 to 12 atmospheres which was fed by means of a compressor.

Before reaching the settling chamber the air pressure was lowered by means of two reducing valves, one of which was a precision valve, to a constant value of 3 kg/cm^2; since the pressure fluctuations in the settling chamber were not more than 10 kg/m^2 *during the intermittent state* it was assumed that *the mass flow in the pipe was constant* for any given setting of the valves.

The settling chamber consisted of a cylinder having a diameter of 165 mm and a length of 430 mm. This contained a Honeywell rectifier with three screens of 144, 484 and

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1296 mesh/cm^2 respectively. The air was then led, through a convergent nozzle, into a pipe of 20 mm diameter.

Measurements of average speed were made with a micromanometer made by the Aerodynamics Laboratory of Göttingen, as well as with the usual type of alcohol manometer. Very small differences of pressure were measured with a Statham Transducer Element coupled to a high-precision indicator made by the Honeywell Brown Electronic Company.

The anemometer, manufactured by the Polymetron Company of Zürich, to Dätwyler-Amrein's design, was equipped with an audo frequency micro-voltmeter and a wave analyzer, in addition to a single-beam Dumont oscilloscope with a low-distortion oscillator (20-15,000 cycles/sec), all of which were made by General Radio Company. Some of this apparatus was purchased at the suggestion of Dr. J. Laufer, who last year carried out in this Laboratory some researches similar to the present ones. (In particular he suggested the use of the silicone oil to make the streamlines visible and, also, a modification carried out by Zito for measuring the outlet from the wave analyzer by means of a thermocouple).

The apparatus for measuring the 'intermittence' factor was designed by Ing. Giacinto Zito and is described in the Appendix to this Report. It was fed by a Nobatron Feeder and connected to a Newlet-Packard Electronic Counter.

The recordings were made by the technicians of the Ferrari Instituto Elettrotecnico Nazionale using an Askania-Siemens oscillograph. In the recordings with a single hot-wire (Figs.10-13) the output from the apparatus had a frequency band of about 5000 cycles/sec; in the two-wire recordings (Figs.14-18) it was necessary to forego compensation for thermal lag and lower-class amplifiers were used so that the total output had a frequency band of about 500 cycles/sec. Nevertheless, these recordings also gave some very interesting results.

2. TRANSITION

All precautions having been taken in order to ensure that the airflow at the pipe inlet shall be laminar, observations of the outlet flow are made. As the Reynolds number increases, the outlet flow suddenly becomes intermittent (turbulent zones or 'spots' immersed in the laminar zones). As Reynolds number increases still further, the 'spots' increase in frequency and length until the outlet is completely turbulent (Fig.10).

We can say that in a pipe with laminar inlet flow three régimes are possible, depending on whether *the outlet flow is laminar, intermittent, or turbulent. We can therefore give a first meaning to transition by regarding the intermittent régime as a transition state between the laminar and turbulent régimes.*

There are two characteristics which distinguish the intermittent state from the other two:

(a) *The intermittent nature of the outlet;*

(b) *The rather considerable random fluctuations of pressure in the settling chamber.*

In both laminar and turbulent régimes, on the contrary, this pressure keeps noticeably constant (it may be recalled that the tests were made with constant delivery).

If we examine what happens inside the pipe when a Reynolds number is reached for which the outlet flow is turbulent, we shall find *four different zones*, starting from the outlet; a *laminar* one, an *intermittent* one, one of *incipient turbulence* (with average transitory values which vary with x), and one of *steady turbulence*.

Thus a *second meaning can be given to transition*, namely, that *the intermittent zone and the zone with incipient turbulence may be considered as an internal transition from laminar flow to turbulent flow.*

An essential characteristic of the intermittent zone is the spot; *in the zone of incipient turbulence the remaining, decaying spots are still visible.*

It is felt that this simplified picture illustrates, in a somewhat general way, the mechanism of transition in a pipe.

Nevertheless, it may happen that inside the pipe, for values of Reynolds number which are not too large, some spots will disappear before reaching the end of the pipe, so that the outlet flow is still laminar. This certainly happens for $Re < Re_{crit}$ if some sort of disturbing obstacle, such as small *screens, wires, holes, convergent-divergent zones, steps, or roughness*, are placed adjacent to the inlet. In this case, as Re increases beyond Re_{crit}, transition will still occur in the manner just described, but the intermittent nature of the flow begins and ends more quickly - with respect to Re (see, for example, Fig.8). It seems that for $Re > Re_{crit}$ *the turbulence which is generated by certain kinds of disturbances forms an unstable environment in which the spots grow more easily;* e.g., in Figure 12 (3rd oscillogram) the wake from a diametral wire and the spots overlapping it are clearly evident.

As the present work is mainly descriptive in character, only the results of a single observation are given in the figures here, without any claim to formulation of laws. It is well known that there are several causes of transition, and since their mutual effects are not known, it is possible to draw two substantially different conclusions from two observations made under seemingly identical conditions.

The values of ΔU plotted on the oscillograms should, therefore, be only regarded as indicating orders of magnitude which will allow comparison between one diagram and another (many of these ΔU's are well outside the linear range of the anemometer, which is based on the theory of small perturbations, and in the case of some recordings we also had to neglect compensation for thermal lag).

3. THE 'SPOTS'

In Figure 9 are shown some *photographs of spots* obtained in the experiments with silicone. For $Re = 2150$ it was observed that most of the spots vanished before reaching the end of the pipe, while for $Re = 2270$ this was not so. In both cases the coefficient of resistance of the pipe was markedly greater than should have been the case for laminar flow: in the first case, $\gamma = 0.0120$ instead of 0.0074; in the second case, $\gamma = 0.0124$ instead of 0.0071.

In the photographs and the oscillograms the main *characteristics* of *the spots* are visible, and these will now be described:

1. The spots have *individual characteristics*, i.e. they can be distinguished from the surrounding fluid (Figs. 9 and 10).

2. They involve the whole pipe section (Figs. 9 and 11): this characteristic is *quite important*, and probably it *will be useful also in the study of transition in the boundary layer*. When the Reynolds number has exceeded the critical value some perturbations in the laminar flow begin to appear; it is only when *the perturbation suddenly involves the whole section* of the pipe that the spot appears. This justifies the name of 'burst' which has been given to it by some authorities.

3. They *have a head and a tail* (Figs. 4 and 9): along the axis of the pipe the fluid has greater speed in the head*. When a spot dissolves, first the head vanishes and then the tail (Fig. 9).

4. Inside the spot it is observed that *vigorous mixing* takes place: in Figure 11 (5th oscillogram) some particles are visible, broken up into very small eddies; these reach the wall with a speed that is much greater than the average local speed. This agrees with the Prandtl theory of mixing length**.

5. The spots *advance with the average speed of the flow: they* constitute a *disturbed fluid which translates itself as a whole; it is not just the propagation of a perturbation* (Figs. 14-17). It should be remembered that time is marked on the oscillograms as points in which the intervals correspond to *one-tenth of a second;* by dividing the distance between the two hot-wires (20 cm) by the delay time with which the same spot strikes them, a speed which is very close to the average speed U_m as measured with a Pitot tube is obtained. We refer to the speed of the spot 'front' without taking into account the 'expansion' of the spot during its travel.

6. They have a random distribution (Figs. 4, 9, etc.).

7. *The pressure gradient* along the pipe is steeper in the spots than in the laminar zones. Therefore *the spot behaves like a resilient pad,* and is driven by the fluid which follows it in the direction of the pipe outlet. Thus, when a spot is generated the pressure in the settling chamber increases in the same way as

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*The fact that there is an increase in speed along the axis of the pipe is quite inconsistent with the theory of mixing length. In a private communication, R. Betchor observed that the increase in speed along the axis could perhaps be represented by a diagram of velocity versus deflection, which is unsteady.

**During a discussion, L. Kovasznay observed that there are some regions of speed in the oscillogram which are less than U and which are not turbulent. If the small curvature with which the downward parts of the oscillogram end are considered to be due to the reaction of the amplifier, then in the rising parts there must have been some imperceptible traces of turbulence in the original oscillogram which disappeared in the reproduction. Nevertheless, the fact merits further examination.

in the case of a horn player who inflates his cheeks more in order to produce a stronger sound; when the spot has been ejected the pressure returns to its former value unless another spot has arrived in the meantime.

8. *Each spot has its own energy balance* between the energy that the settling chamber supplies to it by blowing, and the energy that it spends in viscous dissipation. For values of $Re \approx Re_{crit}$ some spots are observed to dissolve after travelling a more or less considerable distance, while, on the contrary, other spots reach the bottom of the pipe (Fig.17; in the 1^{o} oscillogram spots of both kinds are visible: we must remember that U_m is small). As Re increases, the probability of survival of the spots also increases.

4. THE INTERMITTENT STATE OF FLOW

We can construct a *'model' of the intermittent state* by supposing that for some unaccountable reason some spots are formed at certain points in the pipe at random, that these, once formed, propagate themselves unaltered along the pipe, and that the pressure gradient along the pipe adjusts itself to a value appropriate either to laminar flow or to turbulent flow. This is obviously only an approximate picture of the situation, either because in the spots we are far removed from a steady turbulent state or because in the quiet zones the flow is not quite laminar (Fig.10, etc.).

Figure 2, shows, on a log-log scale, the well known curves of coefficient of resistance for a pipe as a function of Reynolds number:

(a) *For laminar flow*

$$\gamma = \frac{16}{Re}$$

(b) *For turbulent flow*

$$\gamma = \frac{0.079}{Re^{1/4}}$$

(This is the *Blasius formula,* valid for $Re < 10^5$). Taking, for example, $Re = 10,000$, we obtain $\gamma = 0.0016$ and 0.0079 respectively; with a pipe of 20 mm diameter we should have the two pressure gradients $dp/dx = 1.2\ kg/m^3$ and $5.8\ kg/m^3$, depending on whether the flow is laminar or turbulent. Figure 3 shows the static pressure along the pipe for the laminar state (curve 1); if a spot is formed which then moves along the pipe the curves will be similar to 2 and 3. It is clearly seen that when a spot is formed there is an increase in pressure in the settling chamber. This pressure fluctuates in a random manner if the spots are formed randomly (Fig.4): these fluctuations should occur when the pressure has a value within the range corresponding to the wholly laminar state and the wholly turbulent state.

Since we are only considering a 'model' of the flow, no account has been taken either of the pressure drop, $\frac{1}{2}\rho U_m^2$, which occurs in the convergent part (the speed in the settling chamber being considered negligible), or of the pressure drop which we should have in the so-called 'inlet length' of the pipe.

With regard to these two pressure drops, the following observations should be noted:

(a) In the tests carried out in the laminar state, *a pressure drop was always observed, rather than a pressure recovery, in the initial portion of the pipe.* This may mean that in spite of the rectifier and of the three screens inside the settling chamber the 'jet' effect at the inlet to the settling chamber persisted. This recovery of pressure brought about a state of *maximum static pressure,* and this could have been the cause of the generation of the spots;

(b) The static pressure drop $\frac{1}{2}\rho U_m^2$ which takes place in an ideal convergent nozzle (rectangular speed diagram at inlet and outlet) can be related to the pressure drop $(dp/dx)l$ which exists along the pipe, viz.,

$$\frac{\frac{1}{2}\rho U_m^2}{(dp/dx)l} = \frac{1}{64}\left(\frac{d}{l}\right)R_e$$

That is, for a given size of pipe the ratio of these two pressure drops is proportional to Re. Thus, *as Re increases a small non-uniformity of the pressure gradient in the convergent part may result in a very pronounced non-uniformity in the pressure gradient in the pipe.* This may be another explanation for the origin of the spots. Furthermore, it confirms the *integral character of the transition, in the study of which the whole aerodynamic circuit must be considered, not only the local conditions.*

In the settling chamber *unacceptable pressure levels* were observed. When, as Re increases, the formation of the spot increases, the pressure in the settling chamber fluctuates, approaching the value of the turbulent state; but, since the presence of many spots along the pipe represents a condition of disturbance which helps the generation of new spots, it can be seen that at a given moment the pressure in the settling chamber may change almost suddenly to a value appropriate to the turbulent state.

Consequently, values of pressure immediately below this value are less probable.

5. INTERNAL TRANSITION

When the outlet from the pipe is turbulent the pressure in the settling chamber stays at a level which is practically constant; that is, the oscillations observed in the alcohol manometer in the intermittent state of flow are no longer noticed.

If we observe the flow at the conclusion of the intermittent state, we find, starting from the beginning of the pipe, a 'laminar' zone, an intermittent zone, and an incipient turbulent zone (Fig.5). In the intermittent zone there are still some pressure fluctuations (shaded part in Fig.5). With further increase of Re a fourth zone of *steady turbulence* is obtained (Fig.6); this is characterized by a *constant pressure gradient.* The spectrum analysis shows that the complete dissolving of the spots, still noticeable in the zone of incipient turbulence, causes the energy density to be shifted from the low to the high frequencies. In the intermittent zone the static pressure measured at the pipe wall shows somewhat small fluctuations.

The *'laminar'* zone at the pipe inlet was, in fact, a microturbulence zone, with an intensity so small that it was not possible to measure it with the manometer at our disposal. It was called 'laminar' because, having left the anemometer and the oscillograph in the amplification conditions which were used for the other zones, we had in that zone a perfectly linear output. With an amplification of 100, however, microturbulence appeared on the screen. The fact must not be ignored, therefore, that many 'laminar' states obtained at $Re > Re_{crit}$ *are 'laminar' only if they are examined under a low-power microscope.*

The microturbulence of the 'laminar' zone was due, presumably, to the screens in the settling chamber and was not sufficiently damped by the action of the convergent nozzle, although this had a ratio of 70 : 1. We will return to this matter in Section 8.

6. THE INTERMITTENCE FACTOR

The simplest statistical quantity in the intermittence phenomenon is the intermittence factor Γ, which is the ratio between the time during which a given condition exists (e.g., a turbulent signal) and the total time. Limiting the measurements to those along the axis of the pipe, Γ turns out to be a function of x and Re. The results of one set of measurements are shown in Figure 5. It can be seen that the values that were obtained are not reliable when Γ approaches unity (the maximum value obtained was 0.66 instead of 1). This divergence is not attributable to the instrumentation, but rather to the method of testing*. It depends on a *definition of turbulence* which has not so far been given in a general form, although many volumes have been written on the subject of turbulence.

Examination of the oscillograms in Figure 10, etc., suggests the following simple definition: The signal having been rectified so that it always indicates greater than zero, in those parts in which the signal remains equal to zero the flow is laminar; if it deviates from zero, the flow is turbulent. The intermittence-measuring apparatus must therefore measure the time during which the signal is greater than zero. However, since it is not possible to have a signal exactly equal to zero (e.g., the ground noise of the amplifier is enough to prevent this), we are compelled to *fix a 'threshold'*, the electronic apparatus measuring the time during which the signal exceeds this threshold. It is then obvious that Γ becomes a function of the threshold value.

The threshold cannot be established at too low a level because the ground noises of the devices themselves and of other extraneous disturbances should be eliminated as far as possible. It is clear, then, that *when the signal is completely turbulent the time during which it exceeds the threshold value is always less than the total time so that Γ will always be less than unity.* This difficulty is accentuated by the fact that as Re increases the turbulence peaks diminish in intensity (see Fig.12, oscillograms 3 and 4) and many of them fall below the threshold.

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*In various discussions we have found that other experimenters have experienced similar difficulties.

Some suggestions for improving this situation have been put forward by Zito. A complete solution may be reached when it is properly understood what is meant by laminar and turbulent flow; the definition may also have *to take into account the derivative of the* signal. The author has tried to give a definition of turbulence in a previous work, but only in *steady* conditions, and these cannot be applied to the present case.

Measurements of Γ have been made by Schubauer and Klebanoff, by deciding personally from an oscillographic recording when the signal was laminar or turbulent.

A possible way of *evaluating* Γ *approximately* is as follows: At a point of the intermittent zone *is measured,* with a Pitot tube on the pipe axis, the *pressure difference* $p_t - p_s$ (average value). If the flow were completely laminar this difference would be

$$\tfrac{1}{2}\rho U_{max}^2 = 2\rho U_m^2$$

If the flow were completely turbulent this difference would be

$$\tfrac{1}{2}\rho U_{max}^2 = 0.82\rho U_m^2$$

If we call Γ the intermittence factor, we shall therefore have:

$$\overline{p_t - p_s} = (1 - \Gamma) \times 2\rho U_m^2 + \Gamma \times 0.82\rho U_m^2$$

$$= 2\rho U_m^2 (1 - 0.59\Gamma)$$

Thus, by measuring the delivery and then U_m at another point of the circuit (where the flow is homogeneous), Γ can be calculated from the previous formula*.

7. INFLUENCE OF THE MEASURING APPARATUS

The transition being a critical state of flow, any disturbance can substantially alter the phenomenon. It is not surprising, therefore, that the introduction of a probe into the pipe will transform the laminar state into an intermittent one, and the latter into a turbulent state.

Clearly seen, for example, in Figures 14 and 15, is the wake of the first hot wire in the oscillogram obtained from the second wire; the oscillograms obtained by increasing the distance between the two wires were not very representative of the excessive disturbance of the wake of the first wire.

In other words, we have the situation where the *measuring apparatus can substantially alter the magnitude of the quantity being measured.* A case in which this effect was

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*J.C. Rotta (Ing. Arch., 1956) has given a rule-of-thumb method for determining Γ, also based on the different values of U_{max}. Two containers are placed at the end of the pipe at different distances from it; one collects the laminar flow and the other the turbulent flow.

quite unsuspected was one in which the static pressure at the pipe wall was measured both with an alcohol manometer and with a Statham Transducer. Under certain conditions, shown in Figure 7, it was observed that the two measurements were in good agreement at six of the measuring stations, while for the remaining three the measurements given by the alcohol manometer were much higher than those obtained with the Statham Transducer. It was found that by *connecting these holes with the alcohol column the latter began to oscillate and the flow in the pipe became intermittent.*

The spots for this intermittent state, of a periodical nature, are shown at the top of Figure 7. The frequencies were different fron one hole to another.

Generally, one must conclude that the frequency characteristics of the measuring apparatus have an effect on the average value measured.

8. METHODS FOR ACCELERATING OR RETARDING THE TRANSITION

The best method of obtaining laminar flow in the pipe for a value of $Re^* > Re_{crit}$ seems to be as follows:

1. It is necessary *to conceive the settling chamber as a pipe* in which a laminar state is established because the value of Re is lower than the critical value. It is sufficient for this purpose to choose the diameter d_c of the settling chamber so that

$$Re^* \left(\frac{d}{d_c} \right) < Re_{crit}$$

   Screens can be put at the inlet to the settling chamber, but the important thing is that the length shall be sufficient to damp out the microturbulence due to the screens as well as the inlet disturbances;

2. The *convergent* part must be designed in such a way that, if the speed diagram is parabolic at the inlet, it will also be parabolic at the outlet. The convergent nozzle with rectangular speed diagram at inlet may be ideal for a wind tunnel, but is not so from the point of view of delaying transition.

Many devices *for accelerating the transition* - i.e., for obtaining flows which were completely turbulent at values of Re only slightly greater than Re_{crit} - were examined.

A very good way to generate spots and favour transition was found to consist of inserting into the pipe a convergent-divergent portion with a double-frustum cone. The range of Re corresponding to the intermittent state of flow is very small and is just above Re_{crit} (Fig.8).

Another method which was found to be efficient for transition consisted in boring the wall near the inlet of the pipe and connecting this *lateral hole with a small convergent-divergent part:* in this additional duct an intermittent state of flow will soon be established which will favour the initiation of the spot in the main pipe. It is, in fact, *a kind of servomechanism* in which the small lateral duct acts as an exciter:

the fact that it acts directly on the boundary layer of the main duct favours its action. With the second method there is a loss of fluid, with the first a large drop in pressure.

In a lesser degree, *screens* located in the cross-section of the pipe were also found to be effective. The microturbulence generated by them establishes in the flow a kind of instability which is favourable to the initiation of the spots (see Fig.8, where the different turbulence generators are compared). The action of the screens can be explained by examining the effect of a single wire. For example, in Figure 12 the oscillograms were obtained by inserting in the pipe a *disturbing wire* with a diameter of 0.2 mm, *placed along a diameter of the pipe*. As Re increases it can be seen that at a given moment there are on the hot-wire, located at 39 cm downstream of the wire obstacle, some *speed oscillations which are almost periodic*, and which are almost certainly related to *Kármán's vortex wake*. As Re increases, the first spots begin to form; these are quite visible in the third oscillogram. They differ from the wake of the disturbing wire not only because they are *of much higher intensity* (compare, for example, the ΔU's of the 1st and 3rd oscillograms), but also for their *global nature* (they reach the wall also, where the effect of the wake has not yet appeared, as is seen in the 5th oscillogram).

In Figure 16 can be seen the effect of a screen inserted into the pipe. The spots superimposed on the microturbulence of the screen are less strong and also longer than if the screen were not there: they gradually intensify, while the microturbulence gradually diminishes (see 2nd wire of the 1st oscillogram). In the second oscillogram (incipient turbulence) are clearly seen, on the 1st wire, traces of spots some of which are still to be seen on the hot-wire. In the 3rd oscillogram are seen a few spots for decreasing values of Re (returning from the state of incipient turbulence to the intermittent one).

9. SINUSOIDAL SPEED WAVES

A singular action of the screens *inserted in the pipe* is their capacity *for generating sinusoidal speed waves inside the pipe*. To judge from their regularity, they are almost certainly acoustic in nature.

The signals recorded in the oscillograms 1, 2 and 3 of Figure 18 are obtained by placing a hot-wire on the pipe axis 1 cm downstream of the screen. The screens, having different meshes (the same sizes of mesh that were used in the settling chamber), produce different frequencies. In the three cases shown Re was different (about 1700) and the speed fluctuations were very small (less than 0.01%). The screens can, therefore, be a cause of noises in the wind tunnel.

The ability of the hot-wire to detect acoustic signals was observed in the experiments illustrated in the 4th oscillogram of Figure 18. The hot-wire was located at the outlet of the pipe and at about 15 cm from it was located a diaphragm with a resonance box. In the oscillogram can be seen the oscillation generated by a shock on the diaphragm received while the oscillations of a preceding shock were still fading. *Reynolds number influences the amplitude of the signal.*

This confirms also the impossibility of obtaining from the hot-wire an answer exactly equal to zero; in fact, besides the ground noise of the amplifier, there is

almost always some external acoustic noise present which is recorded by the wire in the form of acoustical waves propagating along the pipe. These two kinds of disturbance can affect the measurements of turbulence intensity only if this is very low ($< 0.1\%$), but are of much greater importance in the measurement of the intermittence factor.

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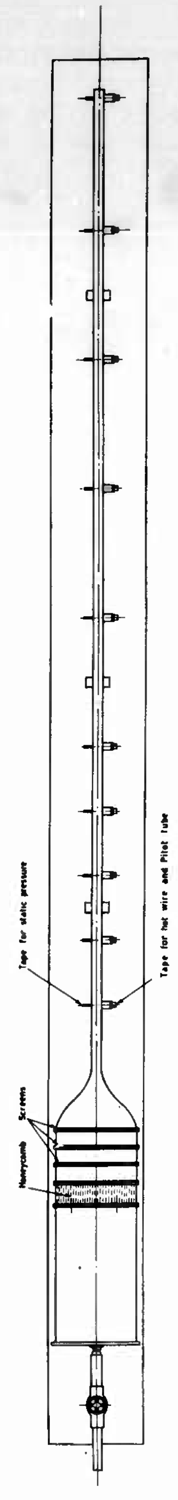

Fig.1 Settling chamber and tube

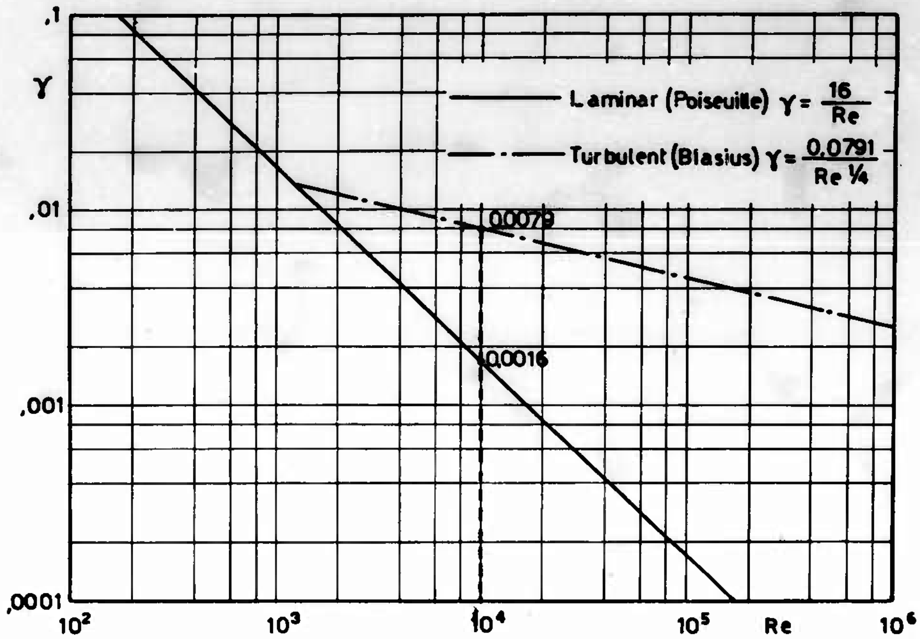

Fig.2 Coefficient of friction for a pipe as a function of Reynolds number

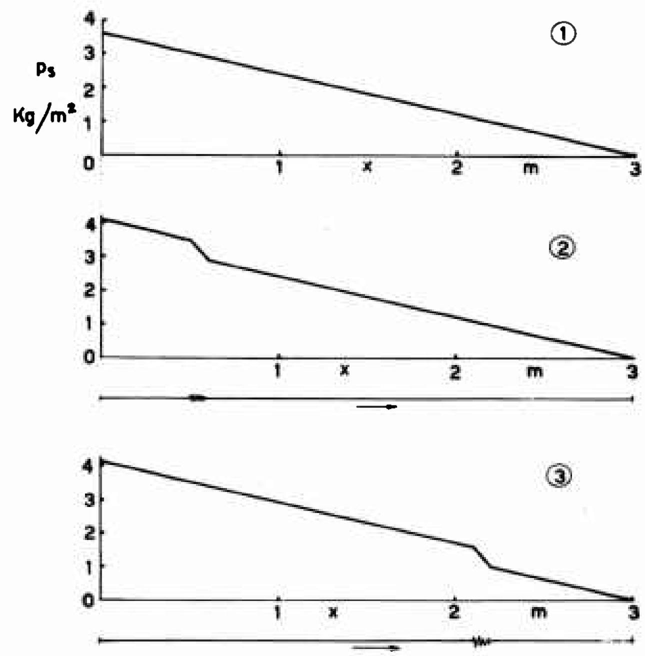

Fig.3 Static pressure distribution along pipe in laminar flow or with a 'spot'

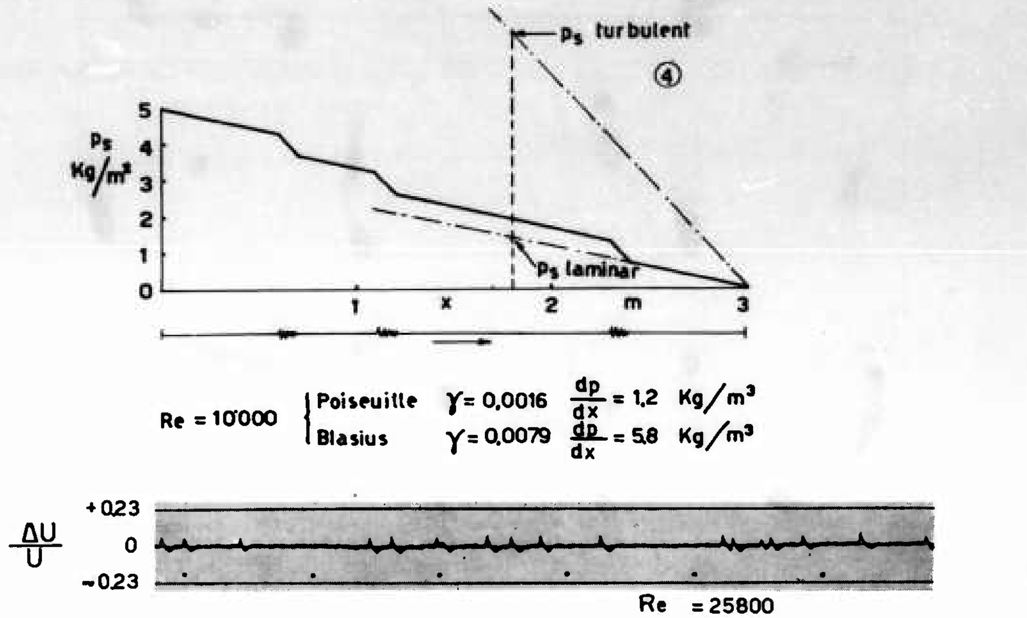

Fig. 4 Random fluctuations of static pressure settling chamber and along pipe; at the bottom: random formation of spots (l = 203 cm, x = 44 cm, y = 1 cm)

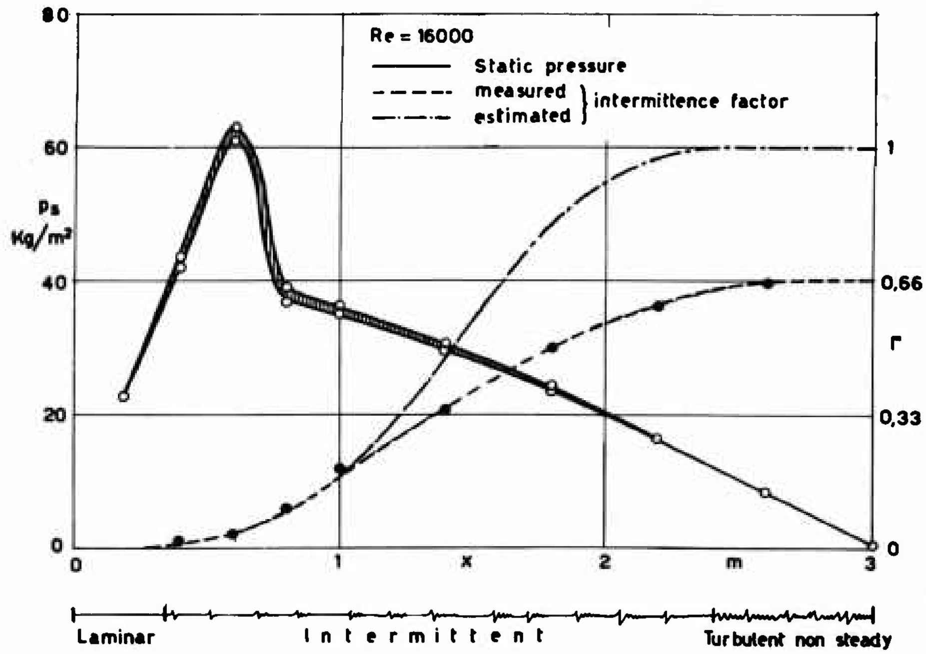

Fig. 5 Régime of incipient turbulence at end of pipe

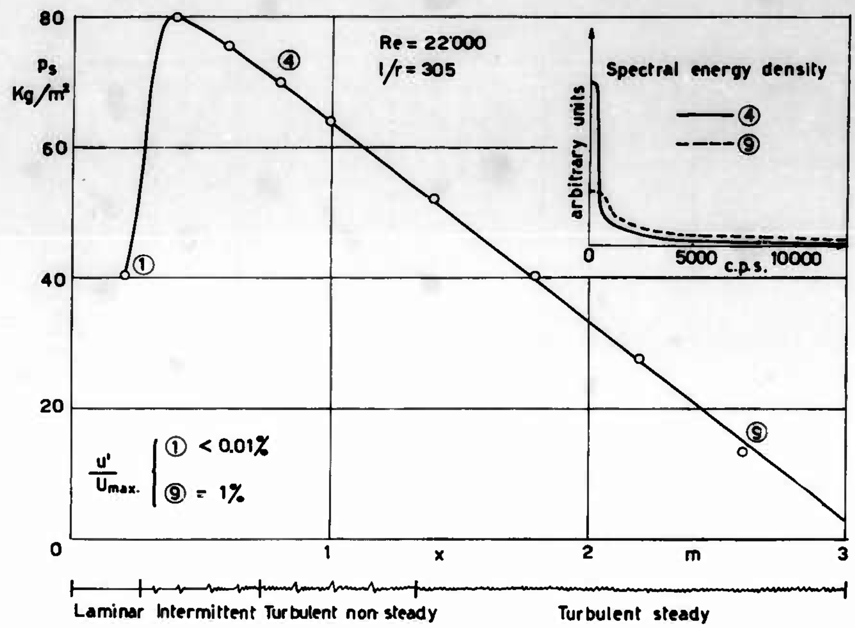

Fig. 6 Turbulent flow régime. Transition zone as a zone of intermittence with a zone of incipient turbulence

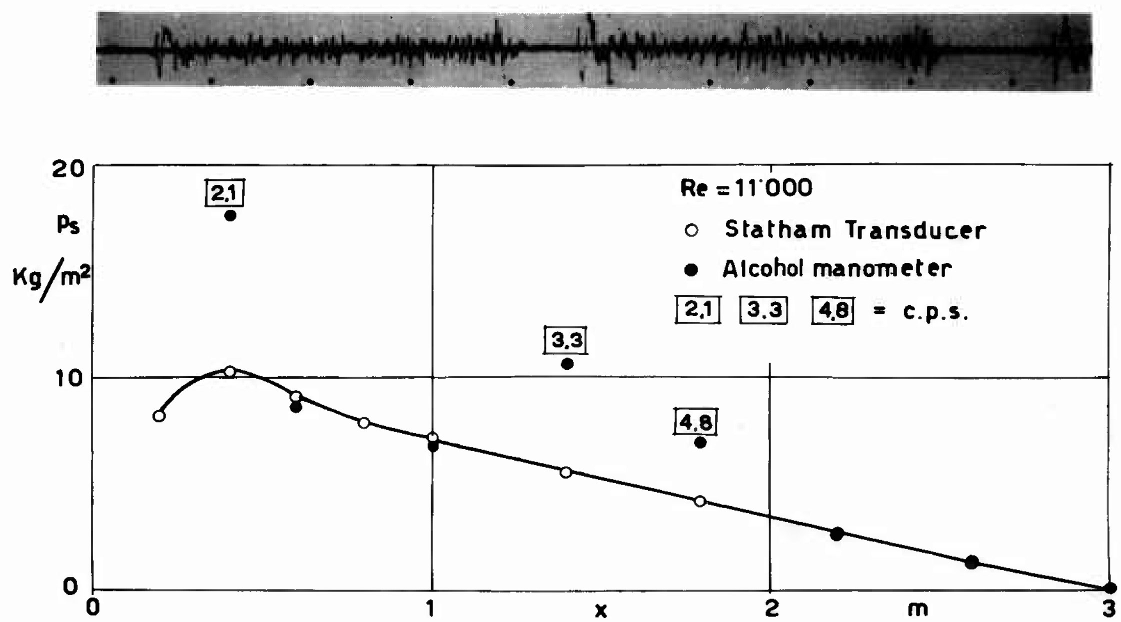

Fig. 7 Static intake connected to alcohol manometer altering flow in pipe by generating periodic spots

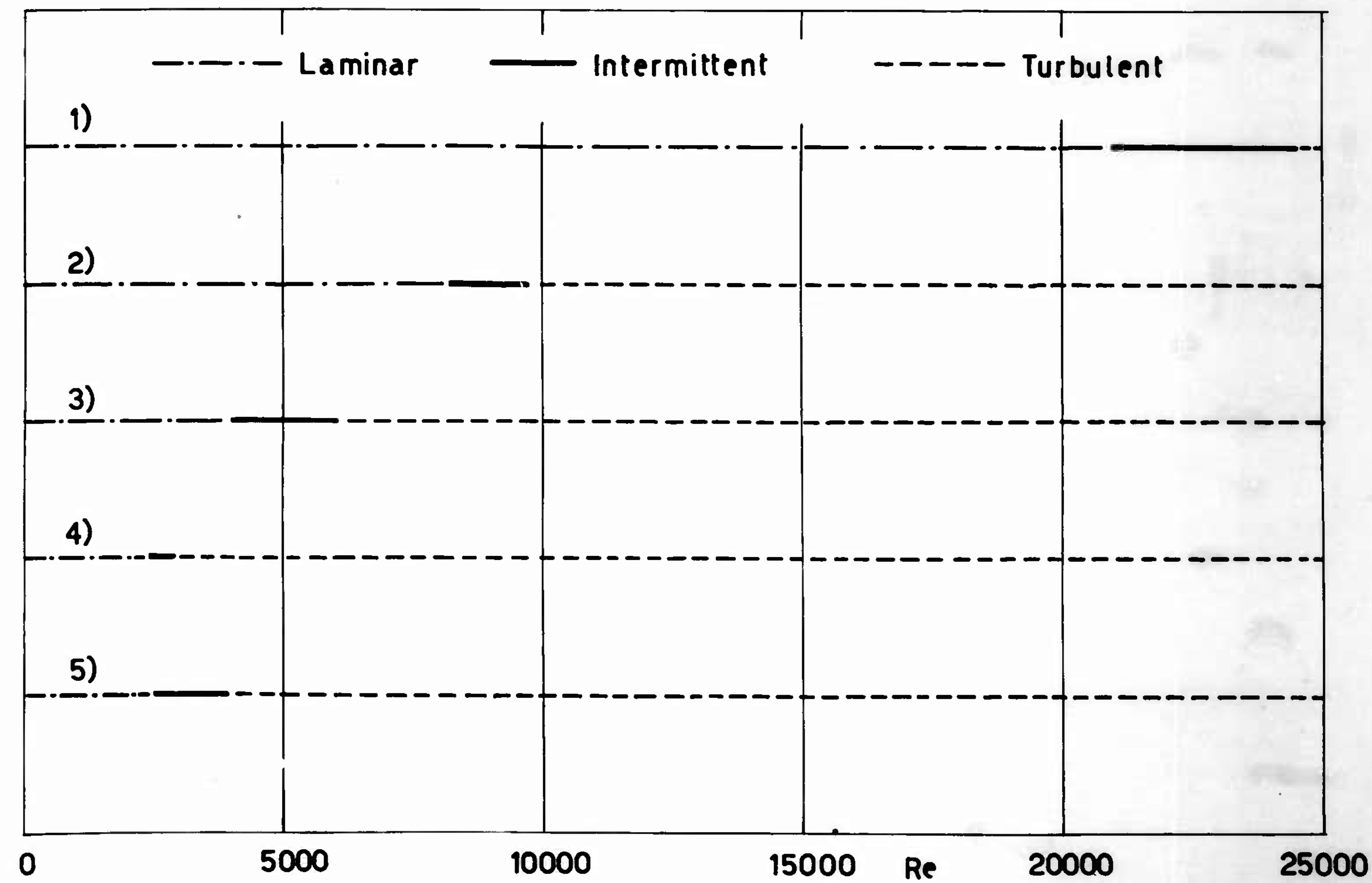

Fig. 8 Limits of intermittent flow régime in certain experiments

(1) with settling chamber
(2) with settling chamber and 0.2 mm dia. wire located diametrally with respect to pipe at x = 5 cm; (l = 203 cm)
(3) with screen in pipe
(4) with convergent-divergent portion or with side excitation
(5) without settling chamber

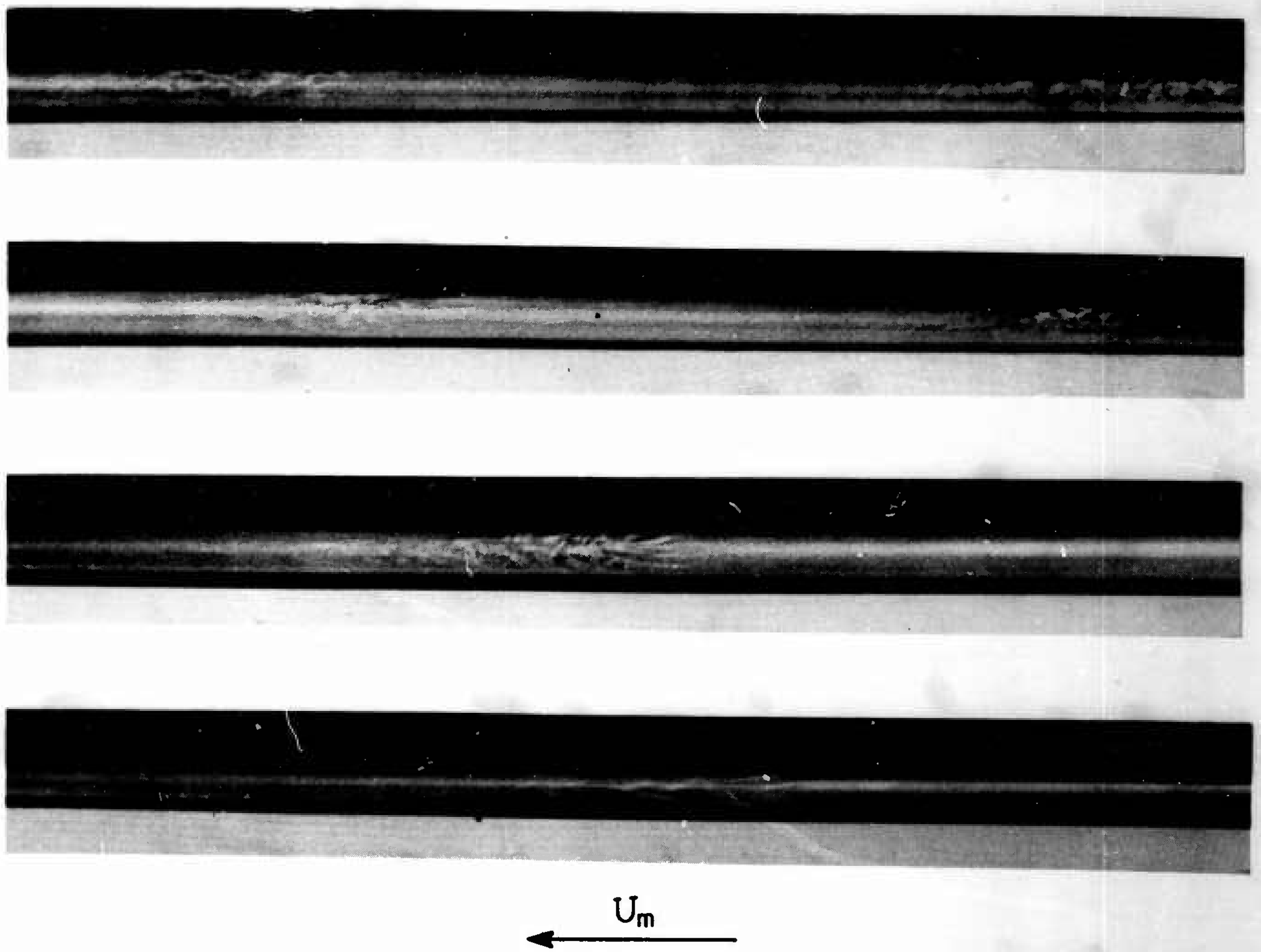

Fig.9 Photographs of spots. In the third photograph the head and the tail of the spot are clearly visible; in the fourth a spot which is dissolving

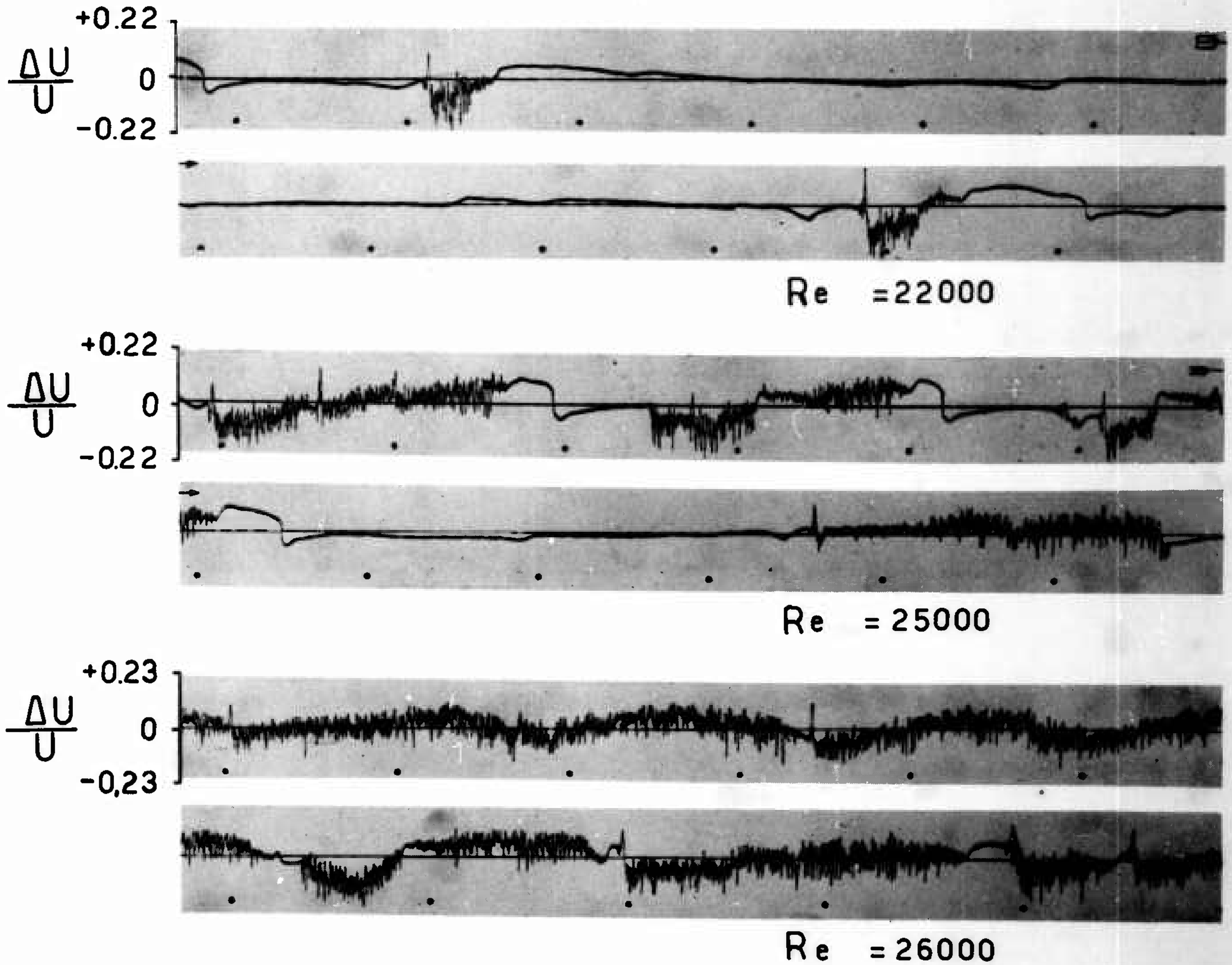

Fig. 10 Intermittent flow with increasing Reynolds number. In the intermittent state of flow as Re increases the spots become longer and more frequent (wire along axis of pipe, x = 180 cm, l = 203 cm)

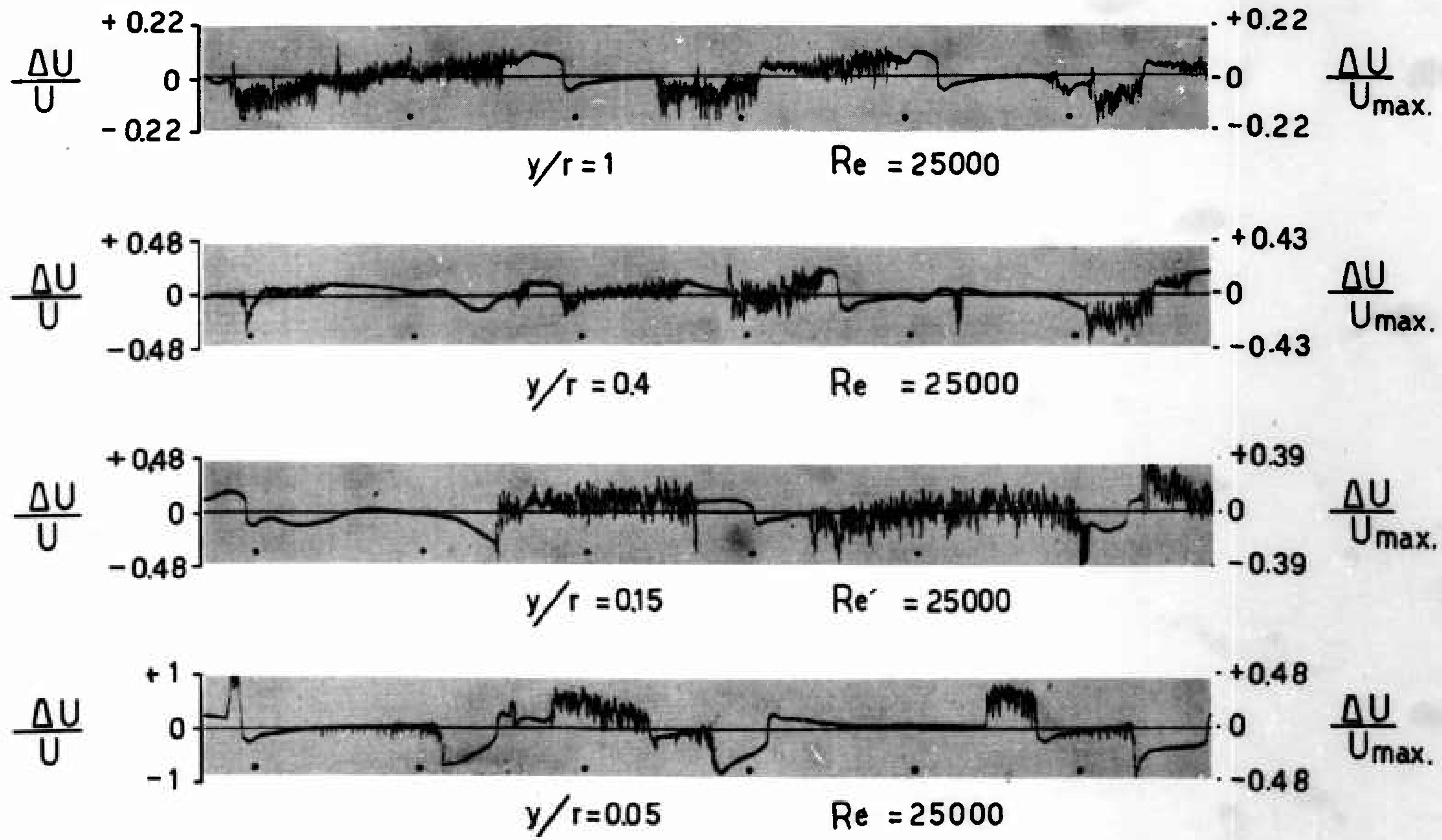

Fig. 11 Variation of speed near wall and centre of pipe with spots. In spots the relative variation of speed is much higher near wall than at centre of pipe (x = 180 cm, l = 203 cm)

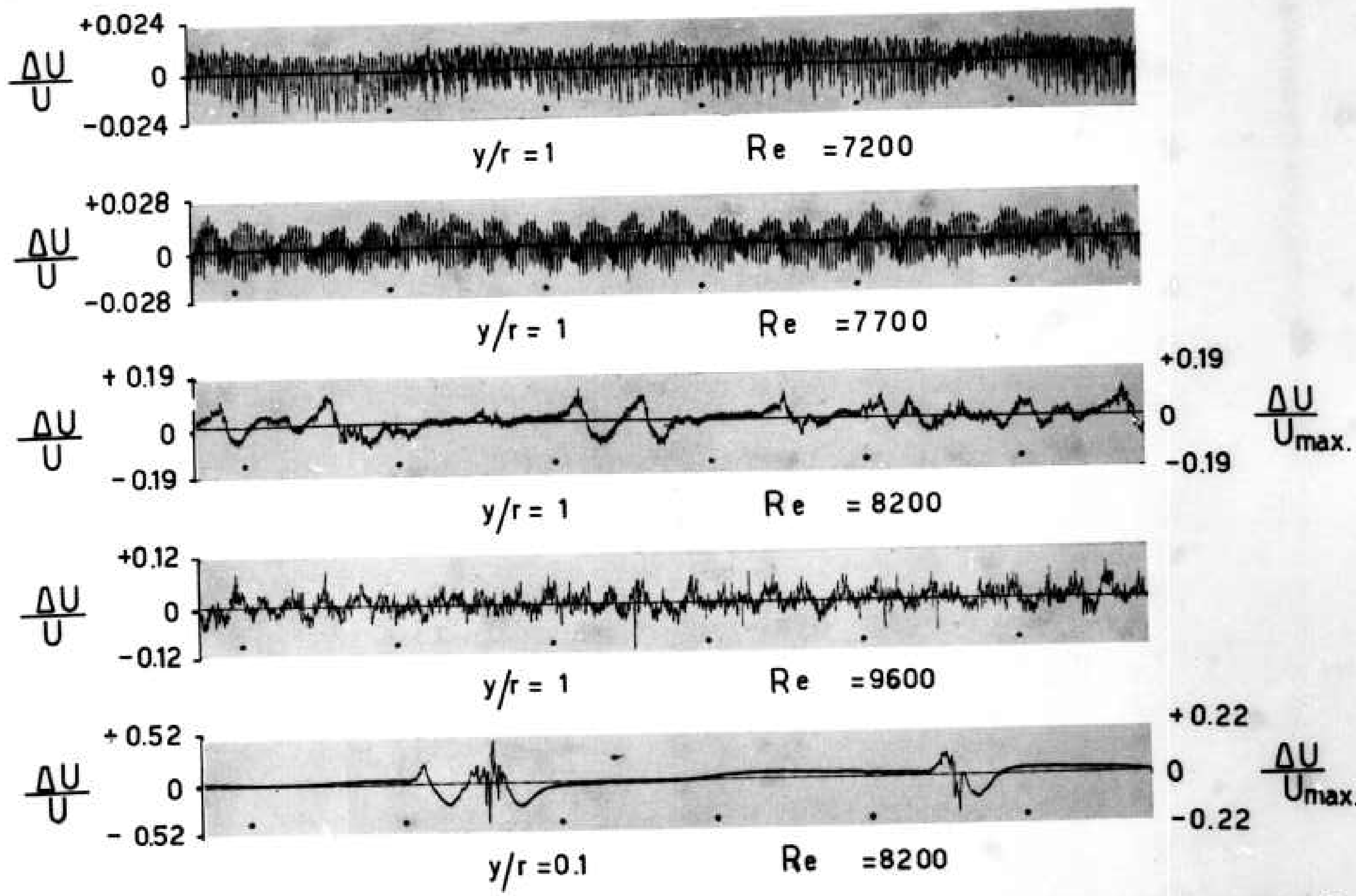

Fig.12 Effect of diametral location of wire with respect to pipe. A wire, dia. 0.2 mm, has been located diametrally with respect to pipe (x = 5 cm); hot-wire at 39 cm downstream of it; l = 203 cm. Oscill. 1,2: Kármán's wake, with high frequencies. Oscill. 3: spots overlapping wake. Oscill. 5: spots come near wall, wake does not

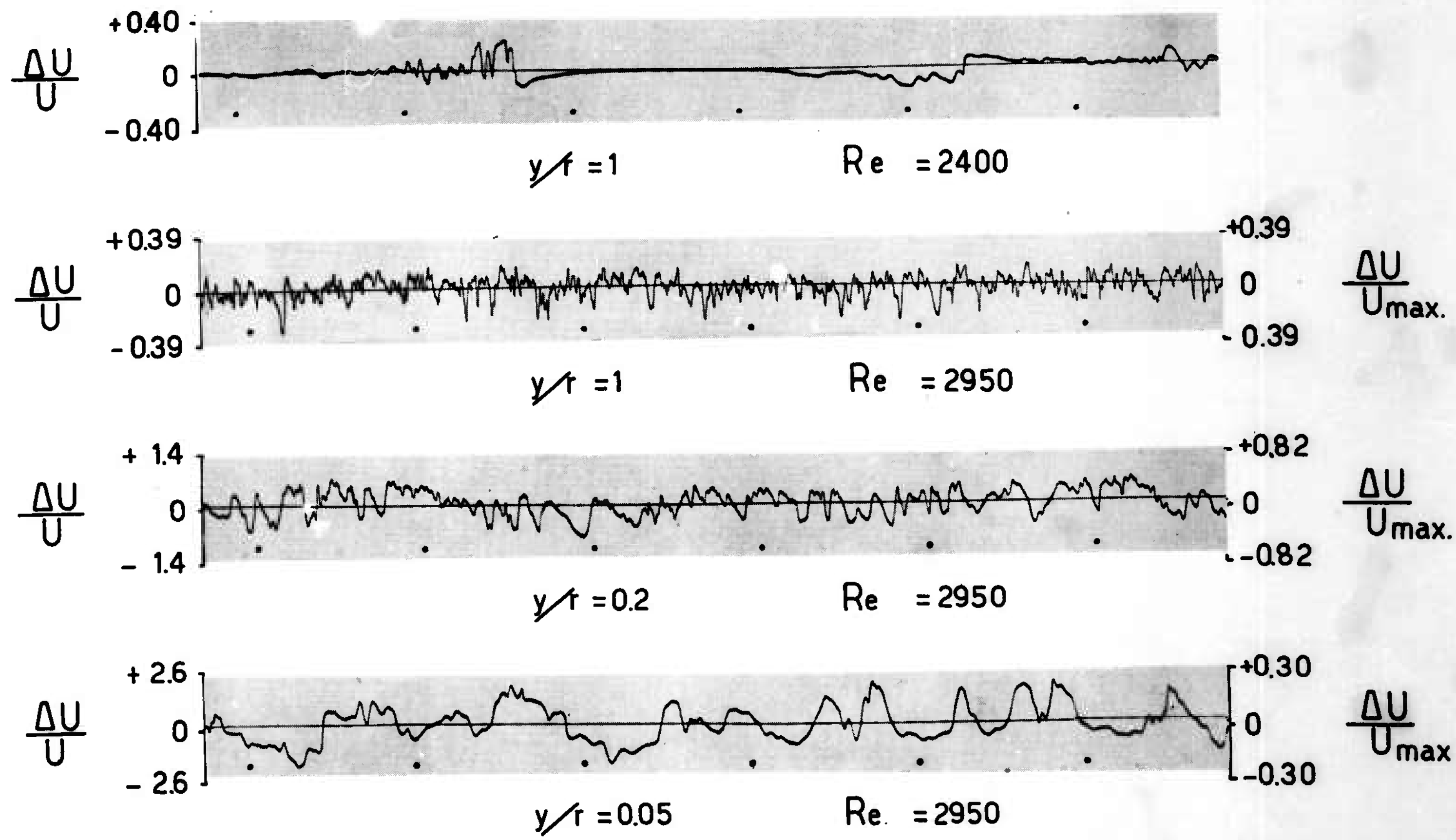

Fig. 13 Intermittent state of flow without settling chamber. In incipient turbulence fluctuations have higher frequencies at centre of the pipe than near wall (2nd, 3rd, 4th oscill.) (hot-wire at x = 44 cm, l = 203 cm)

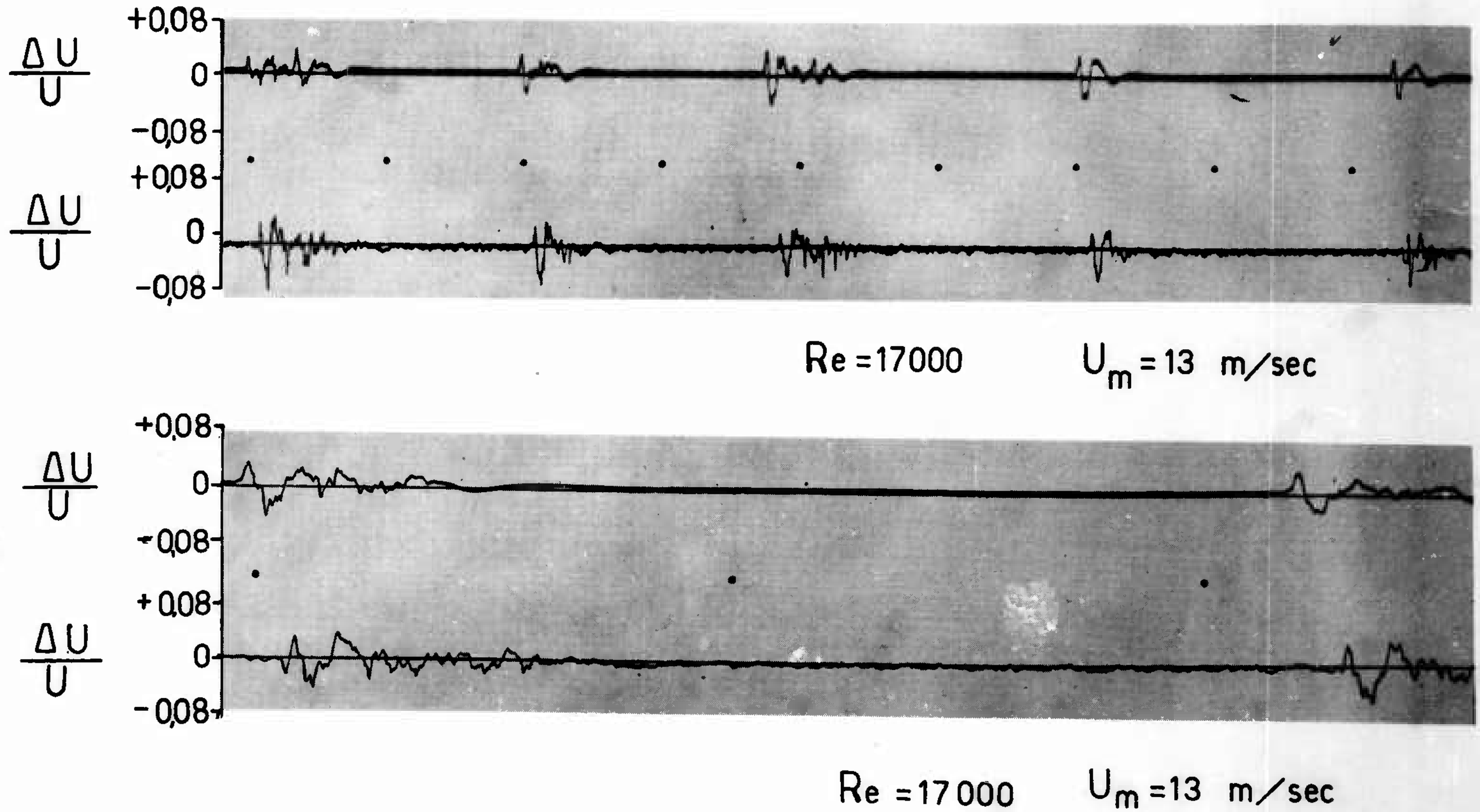

Fig.14 Propagation of spots with average speed of fluid (Re = 17,000) (x_1 = 60 cm; x_2 = 80 cm; l = 300 cm). On the second hot-wire (the lower one in each oscillogram) is visible the wake of the former. In the 2nd oscillogram the speed of the recording tape has been increased

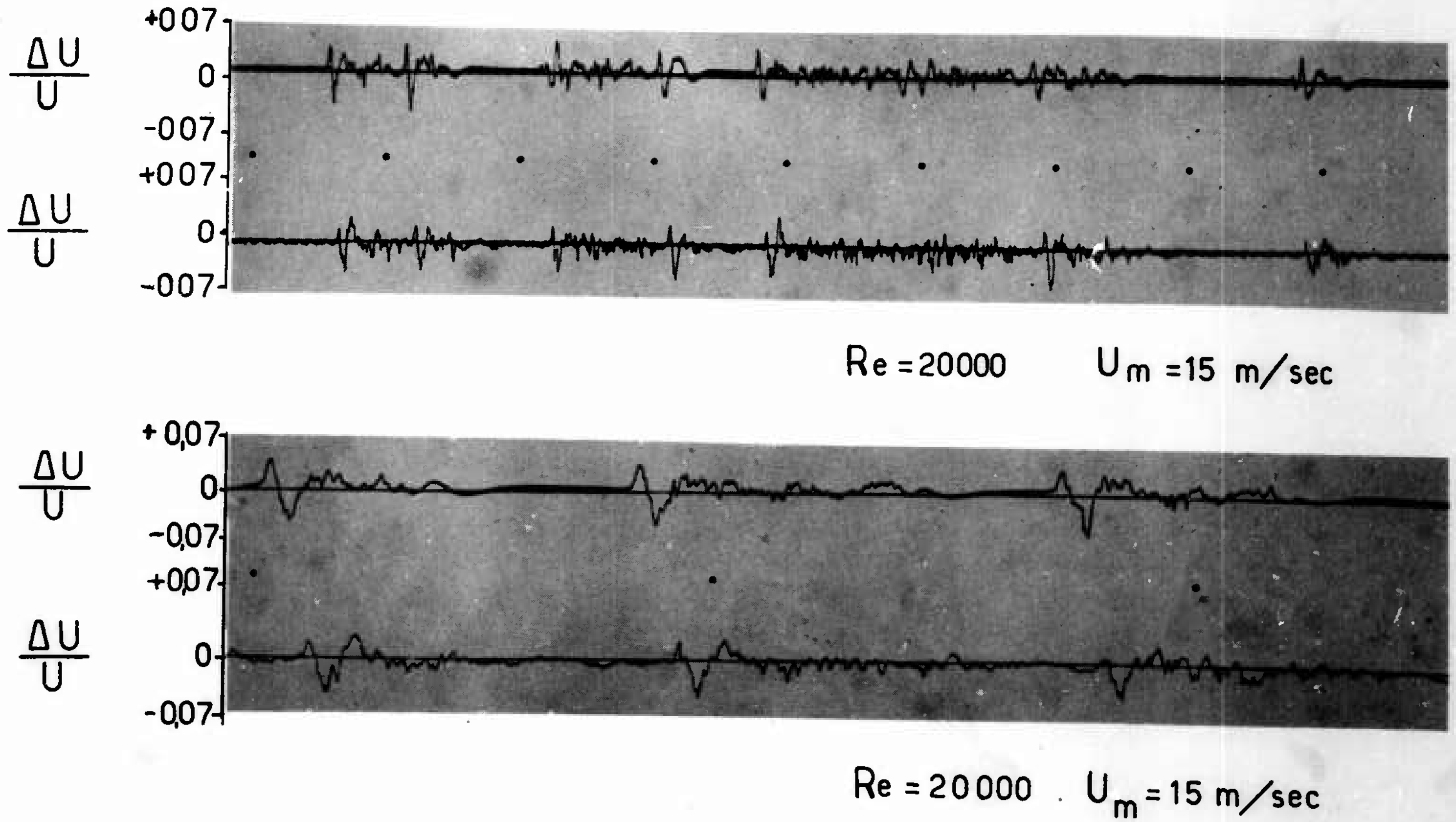

Fig.15 Propagation of spots with average speed of fluid (Re = 20,000) (x_1 = 60 cm; x_2 = 80 cm; l = 300 cm). On the second hot-wire (the lower one in each oscillogram) is visible the wake of the former. In the 2nd oscillogram the speed of the recording tape has been increased

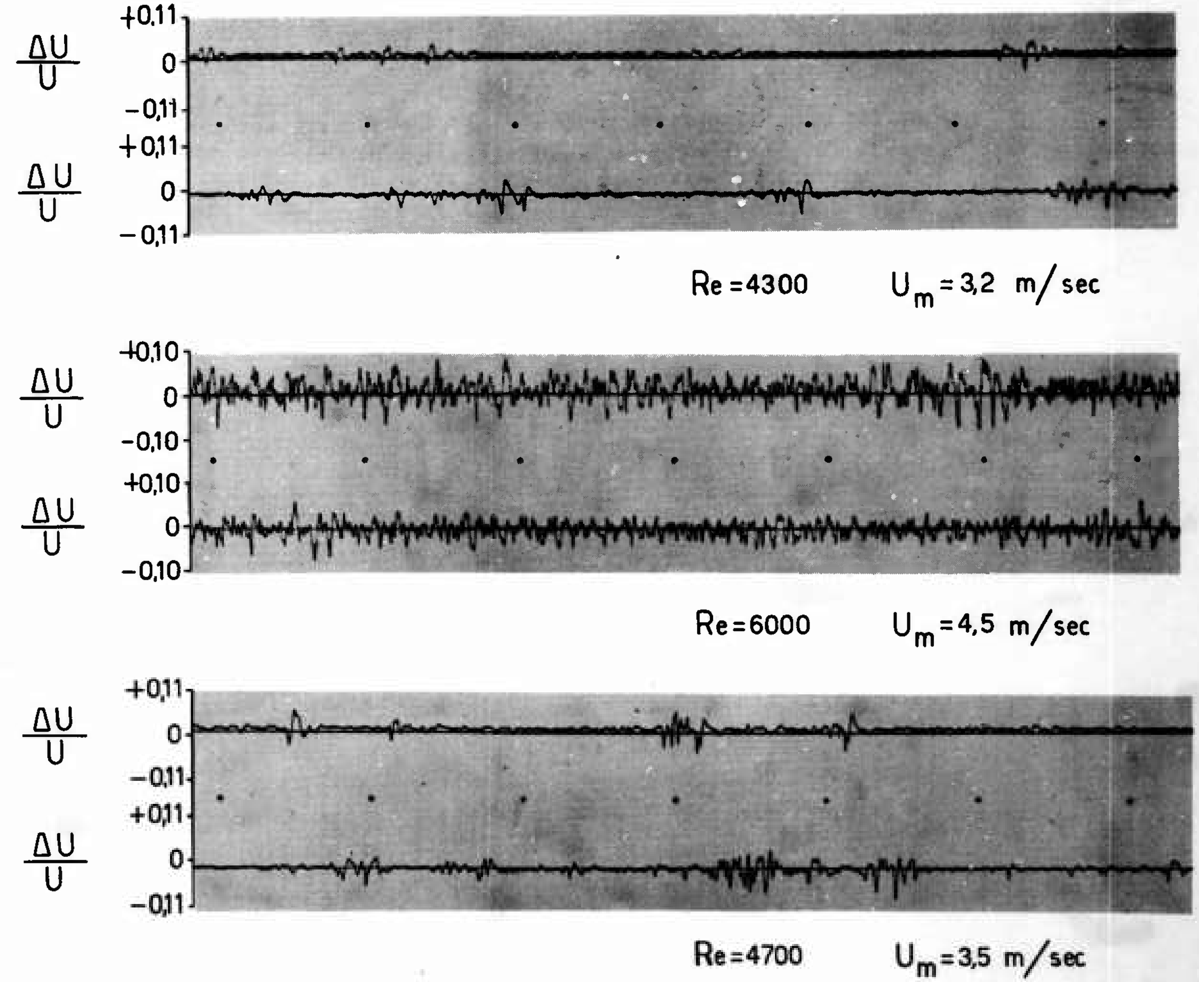

Fig. 16 Screen Microturbulence. A screen with 144 mesh/cm^2 has been located in pipe at $x = 42$ cm ($x_1 = 106$ cm, $x_2 = 126$ cm, $l = 366$ cm; wires on axis of pipe). Spots and screen microturbulence (1st Oscill.). Incipient turbulence (2nd Oscill.)

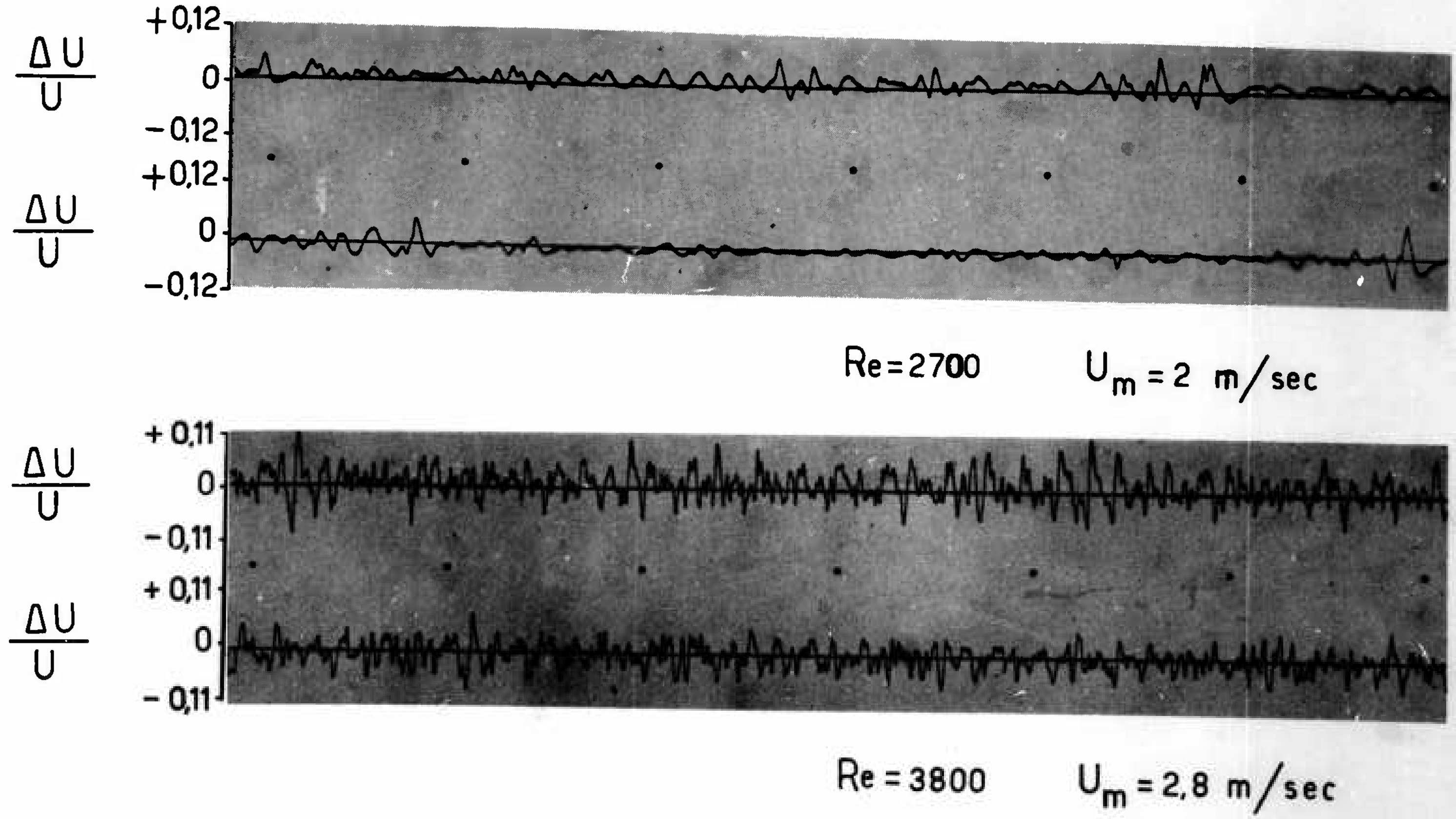

Fig. 17 Effect of inserting convergent-divergent section in pipe. Convergent-divergent portion with two frustums of cone has been inserted in pipe (groove of 8 mm at $x = 5$ cm; $x_1 = 102$ cm, $x_2 = 122$ cm, $l = 362$ cm; wires on axis of pipe). Spots increasing and spots vanishing along path from 1st hot-wire to 2nd hot-wire (1st Oscill.). Incipient turbulence (2nd Oscill.)

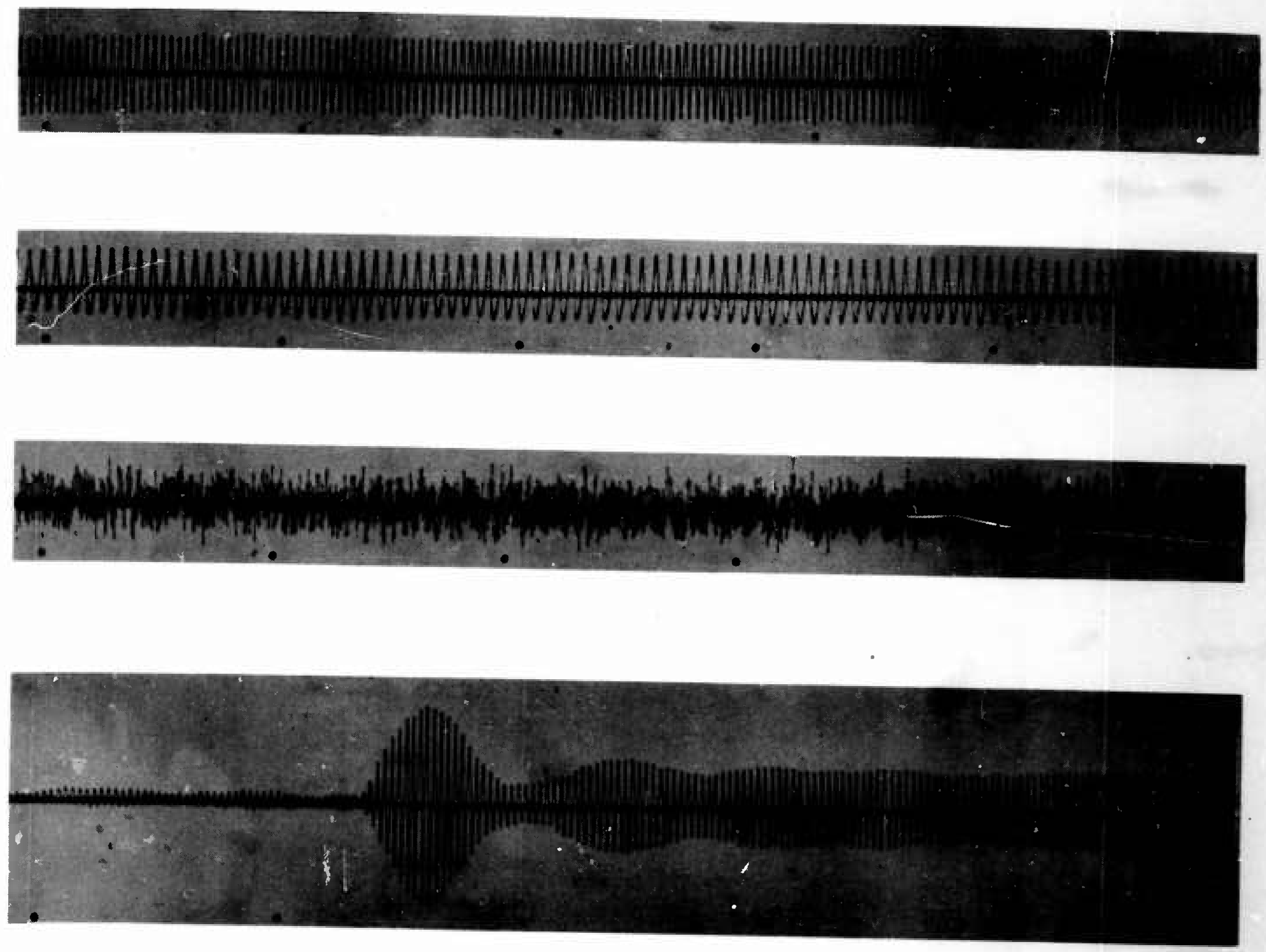

Fig.18 Sinusoidal speed waves due to insertion of screens. 144, 484, 1296 mesh/cm^2 (1st, 2nd and 3rd Oscill.); (hot-wire at $x = 43$ cm on axis of pipe; screen at $x = 42$ cm; $l = 376$ cm). 4th Oscill. was obtained by means of a diaphragm ($l = 46$ cm, $x = 43$ cm, diaphragm: $x = 60$ cm)

APPENDIX

An Electronic Instrument for the Measurement of Intermittence Factor with Hot-Wire Anemometers

Giacinto Zito

1. INTRODUCTION

An electronic instrument to measure the intermittence factor in the transition from laminar flow to turbulent flow has been designed (Fig.19). The first measurements have been obtained for an incompressible fluid in cylindrical, smooth, straight tubes with circular cross sections. The assembly is shown in the block diagram of Figure 20.

A dry air jet, after having passed through a settling chamber, is injected into the tube. The speed of the fluid is increased from time to time by regulating the inflow into the settling chamber, in order to produce in the tube a gradual transition from laminar to turbulent flow. A Pitot tube with a manometer measures the average speed. In the tube is the hot-wire of an anemometer whose signals, amplified and compensated for the thermal lag of the wire, supply the intermittence meter. The latter sends pulses to an electronic counter, with a frequency of 10 Kc/sec, only during the time intervals in which the flow is turbulent. The counter works as a summation device, that is it adds partial sums. For a given time interval Δt_1, all 10 Kc/sec pulses, which pass through the intermittence meter when the flow is turbulent, are counted. At the end of the time interval Δt_1 the counting is stopped. The counter reading gives the time interval Δt_2 during which the flux has been turbulent. The ratio $\Delta t_2/\Delta t_1$ is the measure of the intermittence factor. For a given tube section, by regulating the fluid speed from time to time, it is possible to draw diagrams of intermittence factor versus Reynolds number. Alternatively, with constant range, the intermittence factor can be measured as a function of the distance from the input of the tube.

2. CIRCUIT

The circuit of the intermittence meter is shown in Figure 21. The output of the hot-wire anemometer is amplified $(V_1 - V_2)$ and the phase inverted $(V_3 - V_4)$. The signal is then applied to a detector (V_6), with a threshold level and a suitable time constant which can be varied in accordance with the waveform. A clipper amplifier $(V_7 - V_8)$ and a Schmitt trigger $(V_9 - V_{10})$ transform the signal into rectangular pulses which drive a gate tube (V_{11}). During the time the gate is open, timing pulses can be summed by an electronic counter. The frequency of the timing pulses is 10 Kc/sec. In order to avoid the gate being opened by noise, the detector has a threshold level which can be varied between 0 and 7.5 volts. Small hermetic accumulators are used as voltage stabilizers for this purpose, and to provide grid bias for the clipper amplifier.

The pulse generator (Fig.22) consists of a neutrally stable multi vibrator - $(V_3 - V_4)$ which drives a blocking oscillator $(V_5 - V_6)$. The latter supplies pulses of 1 μsec to the gate, with an amplitude of 50 volts. The multivibrator can be synchronized with a 10 Kc/sec quartz stabilized oscillator. However, the measurements

were carried out without this improvement because the stability of the multivibrator, during some minute intervals, was considered sufficient.

3. MEASURING METHOD

The measurement of the intermittence factor is affected by three parameters: the signal amplitude, the time constant and the threshold level in the detector circuit. Therefore it becomes necessary to follow a particular method in order to reduce the measurements, as a variation of the above-mentioned parameters could give different results. First, the electronic gate performance must be controlled. This can be carried out by observing with an oscilloscope the signal in the detector circuit (Jack U_1, Fig. 21), and intensifying the trace on the screen of the cathode ray tube with the rectangular pulse supplied by the Schmitt trigger (Jack U_3, Fig. 21). With a sinusoidal low frequency at the input, the oscillogram of Figure 23(a) is obtained; in that figure the threshold level is zero and the time constant is 1.5 msec. In Figure 24(a) the threshold level has been increased to 3 volts.

Because of the reversal of the negative halfwaves it is necessary to introduce a time constant in the detector circuit, if the electronic gate must always be open when a signal is applied to the input. In Figure 24(a), for instance, the time constant is slightly insufficient, because the gate does not remain open at the signal's lowest level. This inconvenience is emphasized in Figure 24(a) because of the threshold level of 3 volts. The corresponding pulses at the input of the counter are shown in Figures 23(b) and 24(b). Because of the high pulse frequency, compared with the period of the sinusoidal signal at the input, it is not possible to distinguish single pulses in Figures 23(b) and 24(b). From the preceding oscillograms it is evident that for a predetermined time interval, with a sinusoidal voltage at the input, the counter can indicate any number if the parameters are varied. This is caused by the relatively long rise and fall time of the half period of the sinusoid distorted by the presence of the time constant in the detector circuit. Fortunately the output of the anemometer consists of a group of waves with short rise and fall time if the wave group is considered as a whole. In Figure 25 is shown a typical oscillogram of the waveform produced by the fluid turbulence, but with negative half-waves reversed (Jack U_1, Fig. 21). The trace intensification indicates the time interval during which the gate remains open. It may be pointed out that a small variation of the signal amplitude cannot appreciably affect the time of the gate opening. The time constant of 1.5 msec is the minimum value to keep the voltage minima above the threshold voltage, in order to maintain the gate open during the group of waves. Higher values of the time constant are not advisable because they reduce the slope, making the measurement more sensitive to the amplitude signal variations.

The amplitude of the signals supplied by the anemometer is slightly reduced with the increasing of the intermittence factor. Therefore it is convenient to regulate the amplifier gain with the intermittence factor by nearly one. The threshold voltage and the time constant must be adjusted in this condition. For the last parameters it is necessary to observe the waveform with an oscilloscope, while the gain is regulated by means of the counter. The gain must be the minimum which gives an intermittence factor of unity when the fluid motion is completely turbulent. Summarizing, the more suitable values of the parameters are as follows:

Threshold voltage	The minimum which removes the disturbing effect of the noise. If possible, it may even be zero;
Time constant	The minimum which maintains the gate open during the whole group of waves;
Amplifier gain	The minimum which gives an intermittence factor of unity with the fluid completely turbulent.

These requirements are interdependent, so that they should be repeated many times.

If the meter is regulated by the method already considered, the same results are obtained if the measurement is repeated several times. A control may be carried out by recording on tape the signals supplied by the anemometer and measuring the intermittence factor several times with the same signals but always repeating the regulations.

4. EXPERIMENTAL RESULTS

Some of the oscillograms, as they can be observed at the Jack U_1 of Figure 21, are shown in Figure 26. If the fluid motion is not completely turbulent, the positive pulse supplied by the differentiating circuit $R_{30}C_{14}$ of Figure 21 (Jack U_4) can be utilized in order to sweep, from time to time, the time base of the oscilloscope.

Figure 27 shows the intermittence factor (Γ) as a function of the Reynolds number (Re) for the case of transition inside a smooth tube 3 meters long. The general arrangement is that shown in Figure 20. The position of the hot-wire is at 0.6 m from the input, in the middle of the tube; the tube has a diameter of 20 mm. The scale of the abscissa is:

$$Re = \frac{U_m d}{\nu}$$

where: U_m = average speed in the tube section
d = tube diameter
ν = kinematic viscosity of the air.

The experimental curve agrees with the theoretical calculations*. The critical value of the speed, beyond which the intermittence factor grows rapidly, is clearly evident.

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*E. Mattioli - Ricerche sperimentali sul meccanismo della transizione - Atti della Accademia delle Scienze di Torino. Classe di Scienze Fisiche, Matematiche e Naturali. Vol. 94 (1959-60), dispensa 6[a]

Fig. 19   Intermittence meter

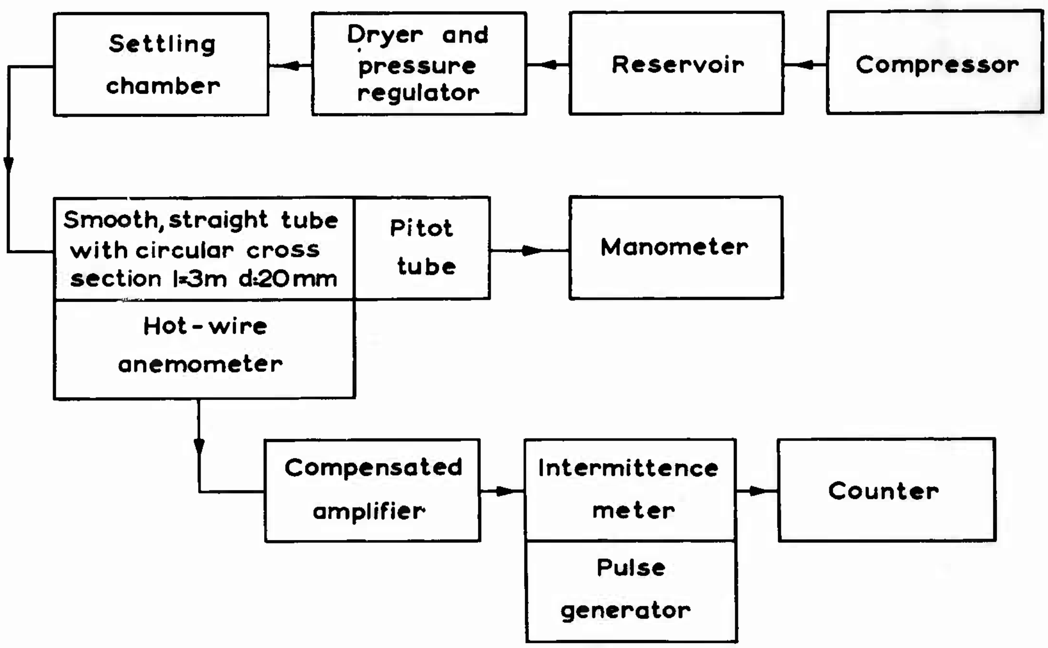

Fig. 20   Block diagram of test set-up

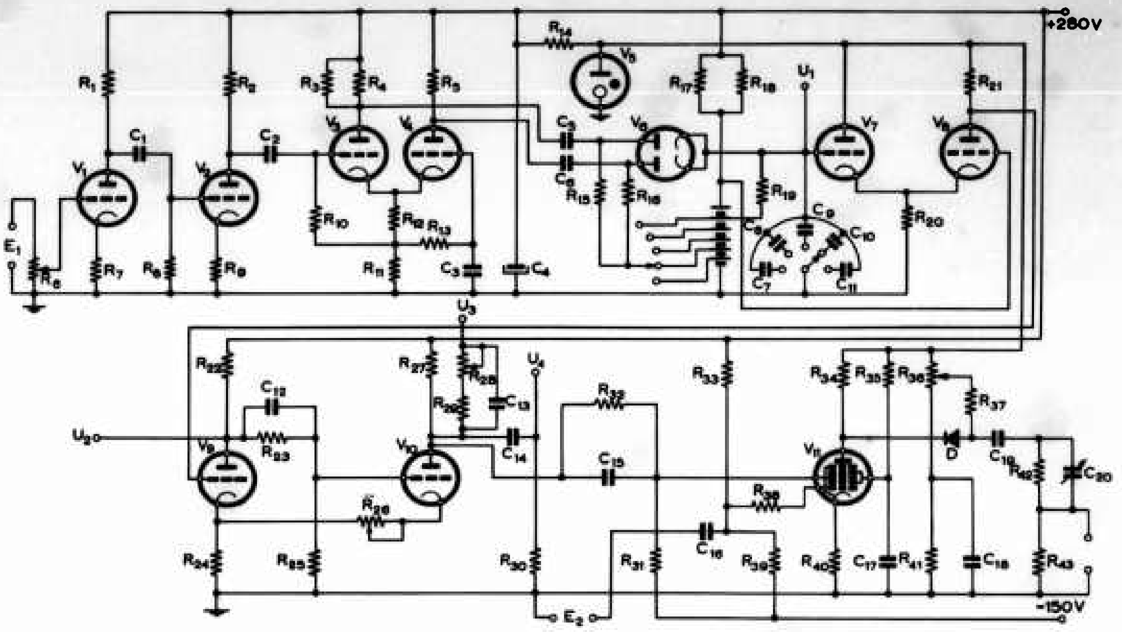

Fig. 21 Intermittence meter circuit

R_1 = 47 kΩ
R_2 = 33 kΩ
R_3 = 150 kΩ
R_4 = R_5 = 22 kΩ
R_6 = 100 kΩ
R_7 = 1 kΩ
R_8 = 1 MΩ
R_9 = 2.2 kΩ
R_{10} = 1 MΩ
R_{11} = 15 kΩ
R_{12} = 2.2 kΩ
R_{13} = 1 MΩ
R_{14} = 6.8 kΩ
R_{15} = R_{16} = 33 kΩ
R_{17} = R_{18} = 47 kΩ

R_{19} = 33 kΩ
R_{20} = 3.3 kΩ
R_{21} = 33 kΩ
R_{22} = 3.3 kΩ
R_{23} = 120 kΩ
R_{24} = 6.8 kΩ
R_{25} = 75 kΩ
R_{26} = 2.5 kΩ
R_{27} = 3.9 kΩ
R_{28} = 2 MΩ
R_{29} = 2.2 MΩ
R_{30} = 10 kΩ
R_{31} = 330 kΩ
R_{32} = 470 kΩ
R_{33} = 560 kΩ

R_{34} = 22 kΩ
R_{35} = 470 kΩ
R_{36} = 50 kΩ
R_{37} = 100 kΩ
R_{38} = 47 kΩ
R_{39} = 270 kΩ
R_{40} = 330 Ω
R_{41} = 100 kΩ
R_{42} = 56 kΩ
R_{43} = 4.7 kΩ

C_1 = C_2 = C_3 = 0.1 μF
C_4 = 80 μF
C_5 = C_6 = 1 μF

C_7 = 0.25 μF
C_8 = 0.2 μF
C_9 = 0.15 μF
C_{10} = 0.2 μF
C_{11} = 0.05 μF
C_{12} = 50 pF
C_{13} = 10 pF
C_{14} = 100 pF
C_{15} = 10 pF
C_{16} = 0.01 μF
C_{17} = 1000 pF
C_{18} = C_{19} = 0.01 μF
C_{20} = 50 pF

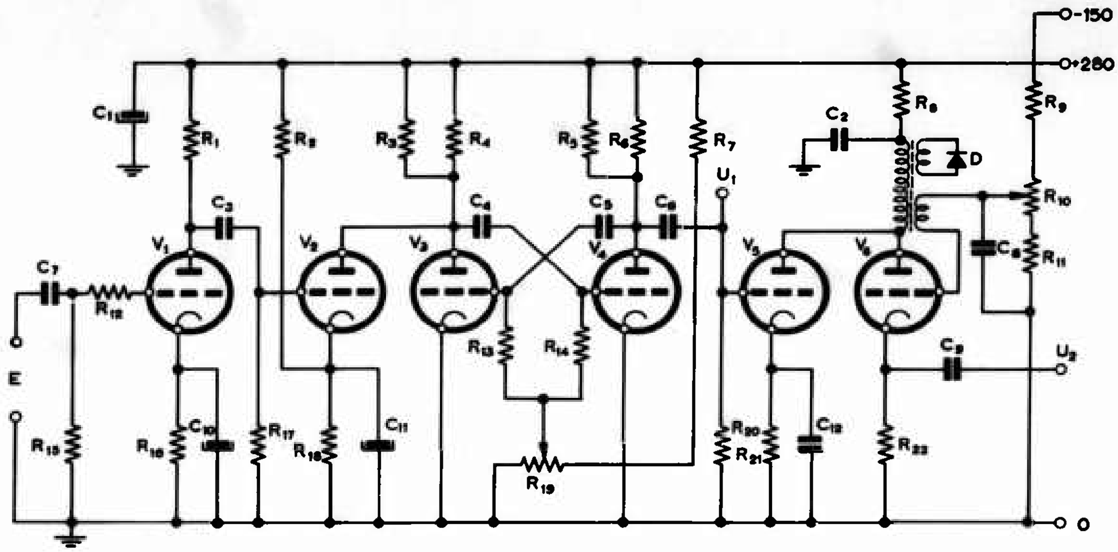

Fig.22 Pulse generator

$R_1 = 100\ k\Omega$
$R_2 = 120\ k\Omega$
$R_3 = R_4 = R_5 = R_6 = 22\ k\Omega$
$R_7 = 33\ k\Omega$
$R_8 = 6.8\ k\Omega$
$R_9 = 120\ k\Omega$
$R_{10} = 50\ k\Omega$

$R_{11} = 4.7\ k\Omega$
$R_{12} = 560\ k\Omega$
$R_{13} = R_{14} = 27\ k\Omega$
$R_{15} = 47\ k\Omega$
$R_{16} = 6.2\ k\Omega$
$R_{17} = 33\ k\Omega$
$R_{18} = 4.7\ k\Omega$

$R_{19} = 25\ k\Omega$
$R_{20} = 56\ k\Omega$
$R_{21} = 10\ k\Omega$
$R_{22} = 220\ \Omega$

$C_1 = 80\ \mu F$
$C_2 = 0.1\ \mu F$

$C_3 = 50$ pF
$C_4 = C_5 = 1500$ pF
$C_6 = 50$ pF
$C_7 = 0.5\ \mu F$
$C_8 = 0.01\ \mu F$
$C_9 = 1000$ pF
$C_{10} = C_{11} = 200\ \mu F$
$C_{12} = 0.1\ \mu F$

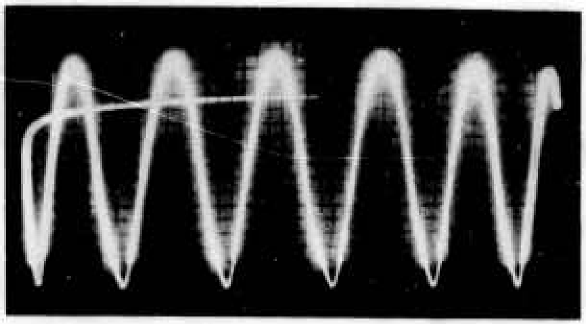

Fig.23(a) Waveform at Jack U_1 of Figure 21. Zero threshold. Sinusoidal signal at the input; time constant 1.5 msec; negative halfwaves reversed

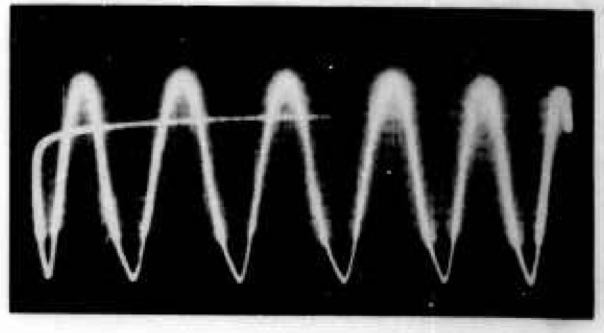

Fig.24(a) Waveform at Jack U_1 of Figure 21. Threshold: 3 volts. Sinusoidal signal at the input; time constant 1.5 msec; negative halfwaves reversed

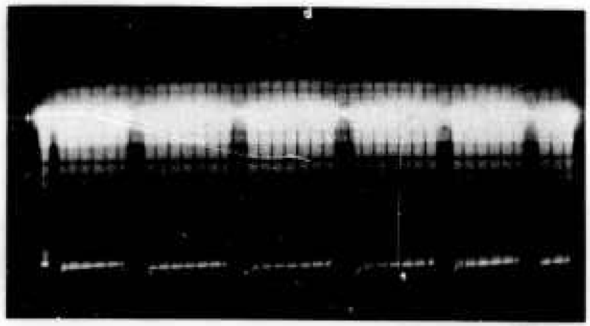

Fig.23(b) Counting of pulses. Zero threshold

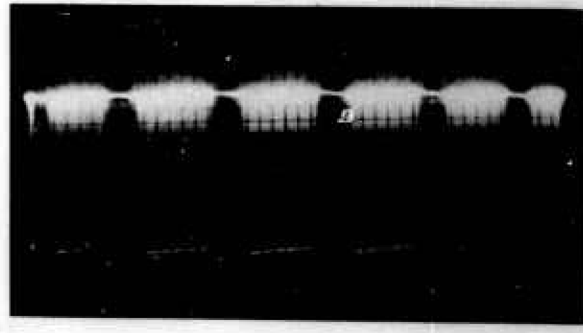

Fig.24(b) Counting of pulses. Threshold 3 volts

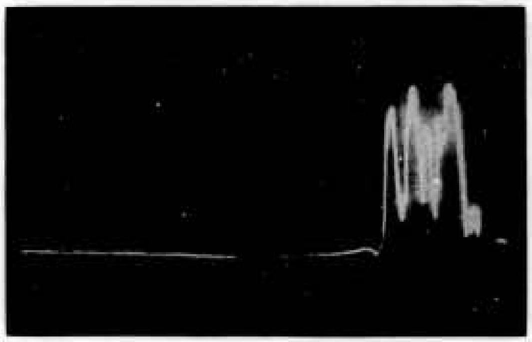

Fig. 25 Group of waves due to turbulence. Time constant: 1.5 msec, negative half-waves reversed

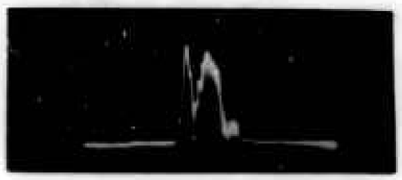

Fig. 26 Group of waves due to turbulence. Threshold 1.5 volts

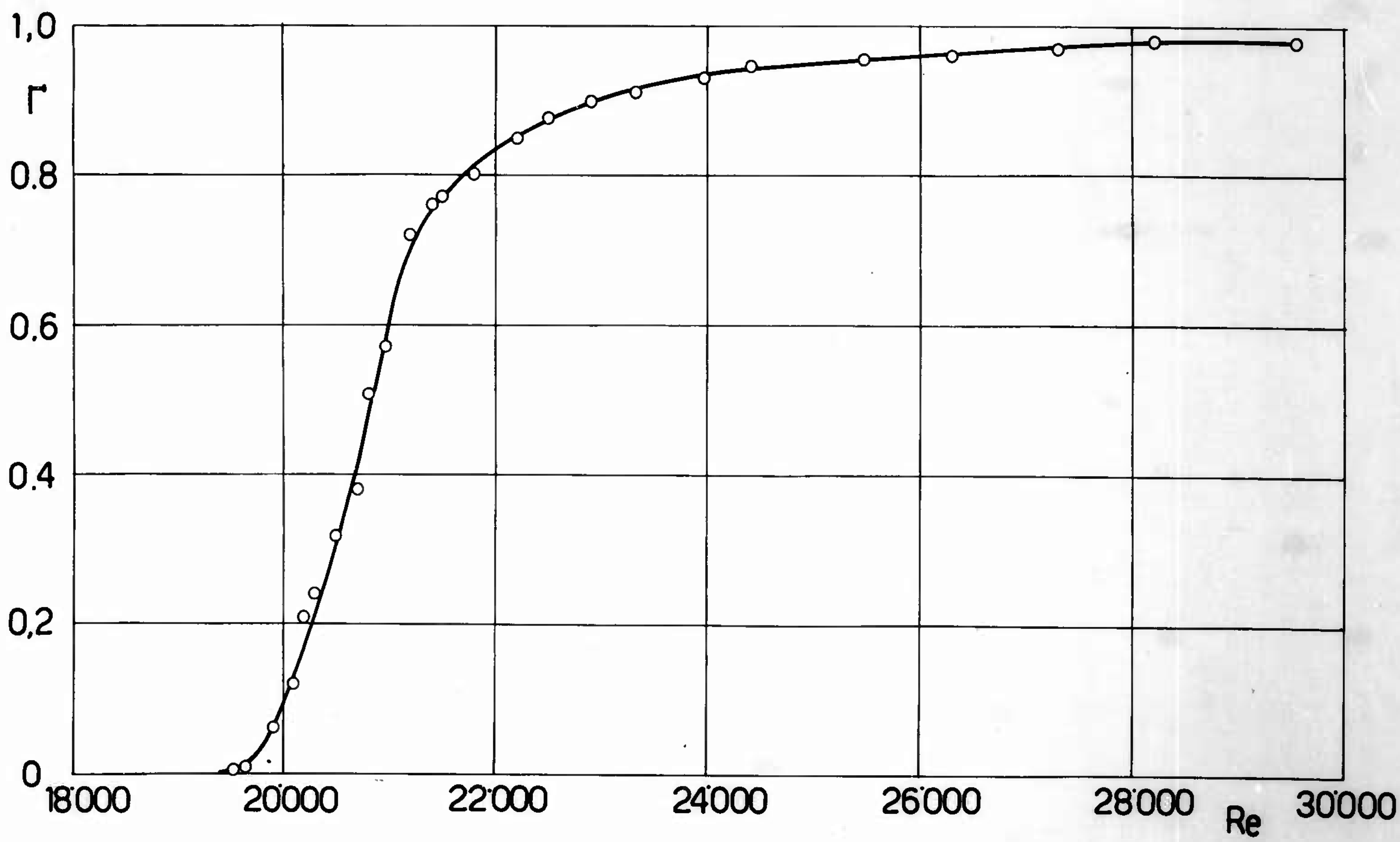

Fig.27 Diagram of intermittence factor versus Reynolds number for a given cross-section

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E.Mattioli and G.Zito
1960
35 pages, incl. 13 refs. 27 figs. & Appendix.

This Report describes experimental research on transition in an incompressible fluid in a smooth straight pipe. At constant delivery there is an intermittent state in which the flow is laminar at the inlet of the pipe and intermittent at the outlet - so-called turbulence spots preceded and followed by laminar flow. The inner transition in the pipe (with laminar inlet and turbulent outlet) occurs

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